Beyond the Burning:
Researching and Implementing Policy Solutions for Sustainable Debris Ablation

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TN-01 A research strategy for evidence-based space policy development

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1 Introduction

This project seeks to establish a comprehensive research framework aimed at mitigating the environmental risks associated with atmospheric ablation of end-of-life spacecraft. By integrating a deep understanding of current atmospheric ablation research with a broad perspective encompassing technical, geopolitical, and socio-ecological factors, we will develop a robust research program with cascading short, medium, and long-term goals. Our focus will be on identifying and addressing critical knowledge gaps and challenges within the field of atmospheric ablation modelling and prediction. This holistic approach will enable us to explore the multifaceted implications of atmospheric ablation and pave the way for the UK to assume a leadership role in space sustainability.

1.1 Scope

This document, TN-01, successfully meets the requirements outlined in Milestone 1 (MS1) by establishing a comprehensive and interdisciplinary framework for investigating the environmental consequences of spacecraft and other space objects re-entering the atmosphere. Building upon the established research strategy, TN-01 delineates an interdisciplinary approach to explore the multifaceted environmental impacts associated with atmospheric ablation.

1.2 Applicable Documents

Applicable documents are identified as ADn, where “n” denotes the document number from the table below.

Ref.	Document ID	Title	Rev.
[AD1]	G23A.001.PP.01	Project proposal	N/A
[AD2]	G23A.001.GFA.01	Fully executed Grant Funding Agreement	N/A

1.3 Reference Documents

Reference documents are identified as RDn, where “n” denotes the document number from the table below.

Ref.	Document ID	Title	Rev.	Date
[RD1]	ST/SPACE/61/Rev.2	International Space Law: United Nations Instruments	2	2017
[RD2]	IADC-02-01	IADC Space Debris Mitigation Guidelines	2	March/2020
[RD3]	United Nations Office for Outer Space Affairs	Long-term sustainability of outer space activities: implementation experiences, opportunities for	1	June/2024

		capacity-building and challenges.		

1.4 Acronyms and Abbreviations

Tag	Description
BNNT	Boron nitride nanotube
CFRP	Carbon fibre reinforced polymer
EoL	End-of-Life
GEM	Gibbs Energy Minimisation
GO	Graphene oxide
LEO	Low Earth Orbits
MEO	Medium Earth orbits
MLI	Multi-layer insulation
TPS	Thermal protection system
VLEO	Very Low Earth Orbits

2 Post Mission Disposal

2.1 Atmospheric Entry and Ablation

The disposal of spacecraft at the end of their missions in Low Earth Orbit (LEO) is a critical aspect of space debris mitigation. The primary approach involves lowering the satellite's perigee, the closest point in its orbit to Earth. This allows atmospheric drag to gradually pull the spacecraft down, eventually causing it to burn up or fragment during re-entry. Two disposal methods utilise this atmospheric burn (ablation): controlled re-entry and uncontrolled re-entry, which are shown in Figure 1.

(a) (b)

Figure 1. Picture of controlled and uncontrolled re-entry. (a) Controlled re-entry of Soyuz capsule; (b) Uncontrolled re-entry of space debris

2.1.1 Controlled Re-entry

In a controlled re-entry, the satellite utilises its propulsion system to manoeuvre itself onto a predetermined re-entry trajectory. This trajectory is designed to target a specific location, typically over a vast ocean area. Controlled re-entries typically employ steeper entry angles, around -1.5 degrees. This steeper angle concentrates the debris footprint within a relatively confined zone. However, steeper angles also result in higher peak heating rates at lower altitudes.

Implementing a controlled re-entry requires maintaining control over the spacecraft, adding significant complexity to the mission. It necessitates extended monitoring, higher costs, and a more demanding overall mission profile. Consequently, controlled re-entries are only undertaken when absolutely necessary, factoring in cost, mission impact, and the difficulty of executing the manoeuvre. Nevertheless, some spacecraft, particularly heavy ones and upper stages of launch vehicles, may have no alternative but to perform a controlled re-entry.

2.1.2 Uncontrolled Re-entry

In contrast, an uncontrolled re-entry occurs passively. Atmospheric drag gradually reduces the satellite's orbital altitude until it reaches a point where the increased drag at lower altitudes forces a final plunge towards Earth. This can happen anywhere along the orbit, making the re-entry location and debris landing zone unpredictable. Uncontrolled re-entries can be further categorized into five distinct orbital groups as:

1. **Nearly circular LEO,** with mean eccentricity e ≤ 0.015, whose evolution is dominated by atmospheric drag;
2. **Low or moderate mean eccentricity (0.015 < e ≤ 0.5)** orbits in LEO, or crossing both the LEO and the medium Earth orbits (MEO) regions, whose evolution is mainly driven by atmospheric drag around the perigee;
3. **High mean eccentricity orbits (e > 0.5)**, whose evolution is driven by luni-solar third body attraction coupled with J_2, but for which the atmospheric drag at the perigee can play an important role at the end of the lifetime;
4. **High mean eccentricity orbits (e > 0.5)**, whose evolution is dominated by luni-solar third body attraction coupled with J_2, with minor influences from solar radiation pressure;
5. **Orbits initially above LEO**, whose evolution is dominated by solar radiation pressure.

The majority of spacecraft at EoL belonging to the first two orbital categories experience a gradual loss of mechanical energy due to atmospheric drag. This translates to a corresponding decrease in their semi-major axis, essentially shrinking their orbit. As these spacecraft reach a point in their orbit where they are nearly circular and have a slightly negative flight path angle, they become susceptible to atmospheric capture. At this stage, their relative velocity typically exceeds 7 km/s. They then descend into denser atmospheric layers, initiating the re-entry process at an altitude between 120 and 110 km.

2.1.3 Re-entry Dynamics and Heating

When the heating rate is sufficiently high, the spacecraft skin or outer components can melt or vaporize. The heating rate depends on the speed at which the satellite descends through the atmosphere, which depends on the ballistic coefficient defined as:

$$\boldsymbol{B} = \frac{\boldsymbol{m}}{\boldsymbol{C_D A}} \left[\frac{\boldsymbol{kg}}{\boldsymbol{m^2}}\right] \quad (1)$$

where m is the mass of a satellite, A is the average cross-section, and C_D is the drag coefficient. Assuming spacecraft follow a ballistic re-entry, the altitude occurs the peak heating during the atmospheric re-entry can be approximated using an empirical atmospheric model as:

$$\boldsymbol{h} = \frac{\boldsymbol{1}}{\boldsymbol{\alpha}} \ln\left(\frac{\boldsymbol{\rho_s}}{\boldsymbol{B \cdot \alpha \cdot sin\gamma_0}}\right) \quad (2)$$

where $\boldsymbol{\alpha^{-1}}$ is a scale height of an atmospheric model, $\boldsymbol{\rho_s}$ is surface density, and $\boldsymbol{\gamma_0}$ is an atmospheric entry angle assumed to be constant.

Figure 2 illustrates the relationship between atmospheric entry angle and the altitude at which peak heating occurs during a ballistic re-entry. The data reveals that as the entry angle increases, the peak heating zone descends to a lower altitude. This is particularly relevant for uncontrolled re-entries, which typically utilise shallow entry angles. Consequently, uncontrolled re-entry vehicles experience peak heating at a higher altitude compared to spacecraft employing steeper, controlled re-entry trajectories.

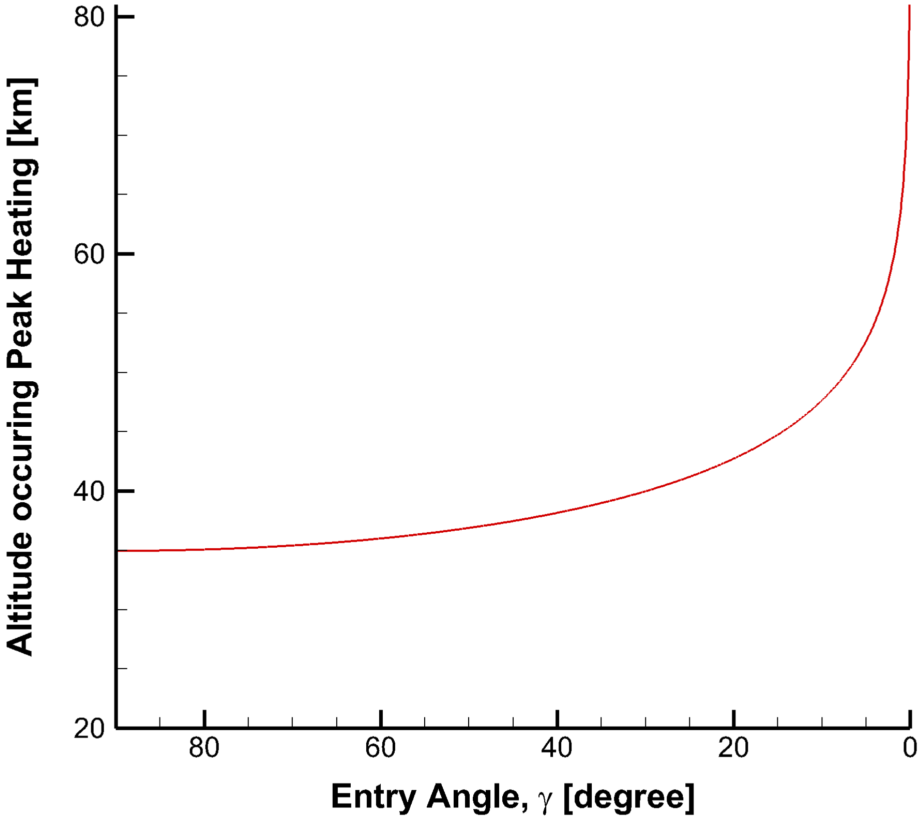


Figure 2. Altitude occurring peak heating during a ballistic re-entry in terms of an entry angle where a ballistic coefficient, B, is assumed as 72 kg/m₂.

Average heating to spacecraft during its atmospheric re-entry is related to its velocity as [1]:

$$\dot{q} = k \cdot \left(2 \cdot B \cdot \alpha \cdot \sin \gamma_0 \cdot \ln\left(\frac{V}{V_0}\right)\right)^{\frac{1}{2}} \cdot V^3 \quad (3)$$

where k is a constant related to the geometry of spacecraft, and V_0 is an initial re-entry velocity. Figure 3 shows the variation in heating rate experienced during re-entry at different re-entry angles, assuming a constant velocity of 8 km/s. It shows a critical trade-off: steeper entry angles induce significantly higher peak heating rates, but these peaks are concentrated over a shorter timeframe. Conversely, shallower entry angles result in lower peak heating rates, but the heating effect persists for a longer duration.

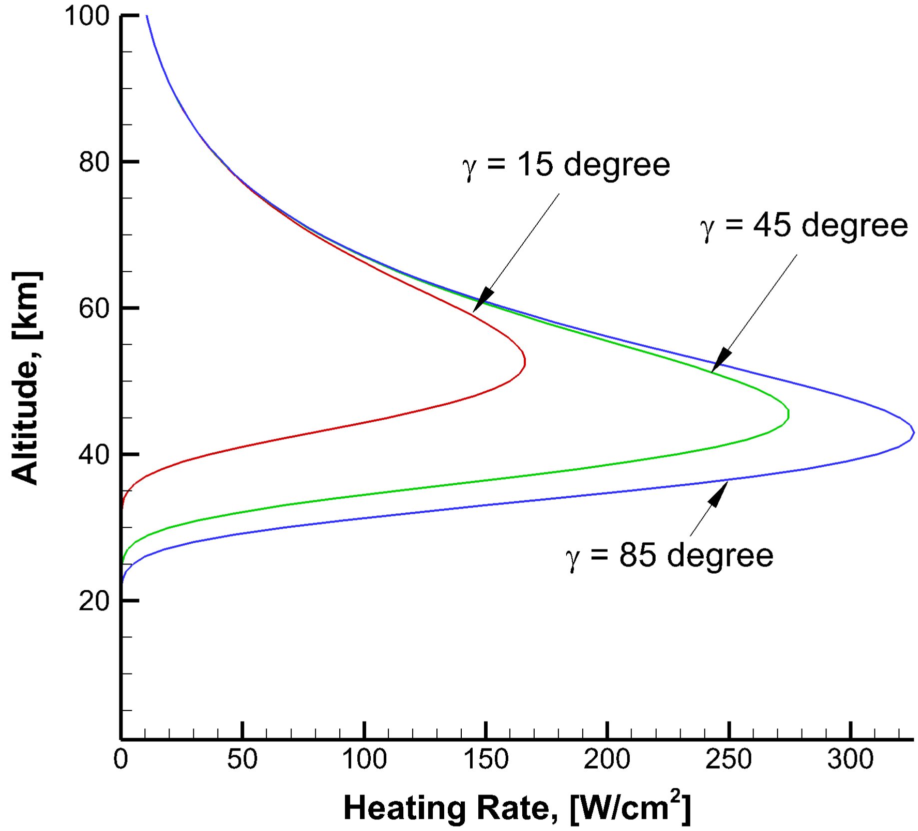


Figure 3. Variation in heating rate at different re-entry angles, where initial re-entry velocity is assumed to be 8 km/s.

In the context of controlled re-entry, a steeper entry angle translates to a very high, but brief, burst of heating. This concentrated heating may have a relatively minimal overall impact on the spacecraft's thermal integrity. On the other hand, uncontrolled re-entry, characterized by a shallow entry angle, leads to substantially lower peak heating rates. However, the extended duration of heating during a shallow re-entry increases the likelihood of the spacecraft absorbing a significant amount of thermal energy.

Heat flux has an important role in material ablation. As shown in Figure 4, the mass and linear ablation rates increase rapidly with the increase of heat flux. The change of the heat flux is related to the ablation temperature and gas velocity and pressure. Larger heat flux leads lead to higher temperature and gas velocity. At the medium temperature around 2,000 ℃, the oxidation of composite material van be occurred as:

$$C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g)$$

$$C(s) + O_2(g) \rightarrow CO_2(g)$$

$$SiC(s) + \frac{3}{2}O_2(g) \rightarrow SiO_2(l) + CO(g)$$

$$SiC(s) + O_2(g) \rightarrow SiO(g) + CO(g)$$

$$SiO_2(l) + CO(g) \rightarrow SiO(l) + CO_2(g)$$

$$SiO_2(l) \rightarrow SiO_2(g)$$

When heat flux is increased, the sublimation and decomposition of SiC matrix can be occurred as:

$$SiO_2(l) + SiC(l) \rightarrow SiO(g) + CO(g)$$

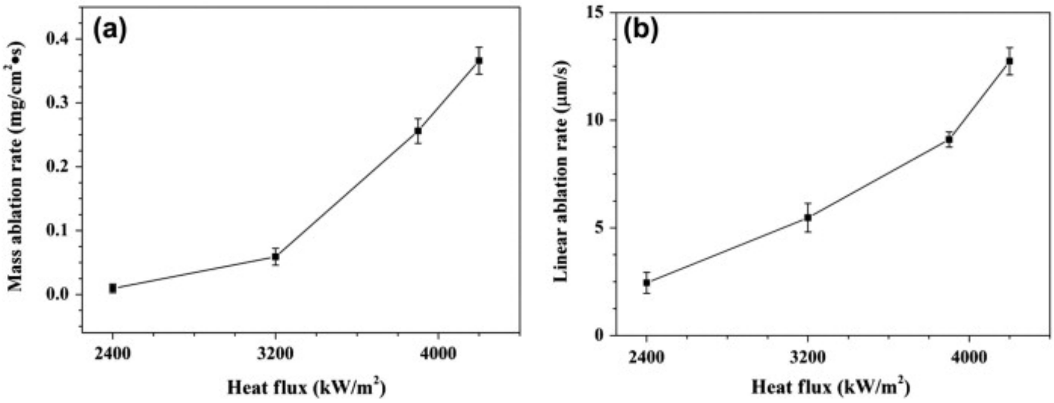


Figure 4. Ablation rates of C/C–ZrB2–SiC composite under different heat flux [2]**. (a) mass ablation rate; (b) linear ablation rate.**

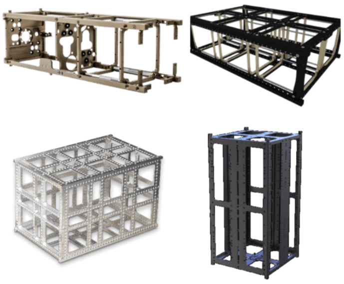
2.2 Modern Satellite Materials

This section describes the materials commonly used in commercial, civil, and scientific satellites, as documented in the literature. Since we have limited information about the materials used in a large number of satellites, including Starlink and military satellites, we assume they utilize similar materials as those found in commercial, civil, and scientific satellites.

Spacecraft continually moving in and out of the sun's direct heat are in constant temperature flux, which can cause it to expand and contract. The materials used in spacecraft can also remain stable in despite the presence of radiation and the vacuum of space. For the parts which require the strength, lightweight and rugged materials like high strength alloys of aluminium, titanium, and stainless steel are used. Aluminium, plastic, and other materials are used for the parts which require specific processing.

2.2.1 Structural system

Figure 5 shows a few satellite structures which refer to the primary and secondary components providing support and connection for various equipment and subsystems on a satellite, including propellant tanks, communication equipment, sensors, and thrusters. The materials of satellite structure are commonly selected with considering strength, rigidity, ductility, fracture toughness, thermal conductivity, corrosion resistance, volatility, and thermal expansion. Aluminium alloys are commonly used in satellite structure as they are strong and lightweight enough to be functional in space structures and spacecraft. Recently, non-metallic materials such as graphite–epoxy composite material are also increasingly utilised for both the primary and the secondary structures to take advantage of their superior mechanical properties.


(a) aluminium alloy


(b) titanium alloy

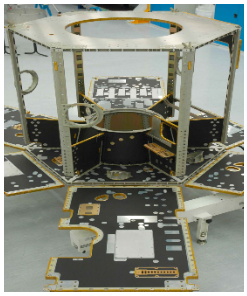

(c) stainless steel

Figure 5. Pictures of satellite structures

Aluminium alloys are prevalent in spacecraft construction due to their favourable strength-to-weight ratio. The most widely consumed aluminium alloys are the Al-Cu-Mg alloys (2000-series), Al-Zn-Mg alloys (7000-series) and Al-Li alloys. 2xxx series aluminium alloys are mainly used where high damage tolerance and fracture toughness are essential features. Machined elements, like ring frames, flanges, fittings, and brackets are made from 7xxx series aluminium alloys. 6xxx series aluminium alloys (Al-Mg-Si) are used when high strength is not a primary requirement. As Al-Li alloys, such as Al-Li AA 2195 and 2050, permit a stronger yet significantly lighter architecture, they are used in joining components and propellant tank domes.

Stainless steels (A286CRES, 302CRES, 305CRES) and **titanium alloys** (Ti-6Al-4V) are also utilised for specific components. Their non-magnetic properties make them suitable for certain applications. While magnesium offers advantages in terms of low density and vibration damping, its susceptibility to corrosion necessitates careful handling. Beryllium has been used on James Webb Space Telescope for the mirrors due to balance of mass and optical performance for infrared. While Beryllium has exceptional specific rigidity and thermal properties, it has limited use due to toxicity concerns on common satellites.

Graphite-epoxy composites dominate spacecraft structural materials due to their exceptional strength, rigidity, and lightweight properties. The graphite fibres embedded in the epoxy matrix provide these desirable characteristics. Moreover, the orientation and content of these fibres can be meticulously controlled to tailor the material's properties, including strength, rigidity, and thermal expansion. Notably, graphite fibres exhibit a near-zero or even negative thermal expansion coefficient, enabling the creation of materials with minimal dimensional changes in response to temperature fluctuations. This makes them ideal for components requiring high dimensional stability, such as antenna dishes. Graphite fibres are categorized into two primary types: high modulus and high strength. The former excels in applications demanding high stiffness and resistance to buckling, while the latter prioritizes strength for load-bearing components.

Aramid (Kevlar)-epoxy composites, a material used in bulletproof vests and armour, are used in spacecraft construction, primarily as face sheets in sandwich panels or shells, where their electrical non-conductivity is advantageous. As Aramid-epoxy composites are an incredibly lightweight and strong material with having incredibly resistant to temperature changes, they are commonly used for the orbiting structures that move in and out of the sun's direct heat as the spacecraft orbits the Earth.

Epoxy-based adhesives play a crucial role in the assembly of satellite structures by bonding independently fabricated composite elements. This bonding technique is prevalent in the construction of composite components featuring metallic end or edge elements. For instance, honeycomb sandwich panels rely on adhesive sheets to secure the face sheets to the core. To reinforce bolt holes and panel edges, the honeycomb voids are often filled with an epoxy polymer infused with silica micro-balloons.

Table 1 summarises the list of common materials using in satellite structures. As can be seen, high strength alloys of aluminium, titanium, and stainless steel have been in common use.

Table 1. List of materials commonly using in satellite structural subsystem

Category	Materials
Metal	• Aluminium alloys 2024-T3, 2219-T851, 2050-T84, 2098-T82, 2195-T82, 2297-T87, 5083-H32, 5083-H38, 5086-H34, 5086-H38, 5456-H32, 5456-H38, 6061-T6, 7075-T73 • Stainless alloys A286 • Nickel alloys Inconel 625, Inconel 718 • Magnesium alloys AZ31B H24 • Titanium alloys Ti-6AL-4V • Other alloys AMS 7906
Non-metal	T800H/epoxy, Kevlar 49/epoxy, E-Glass/epoxy

2.2.2 Thermal control system

Spacecraft have passive thermal control system including a surface treatment, coating, multi-layer insulation (MLI) blanket, sun shield, and thermal strap. Recent conversion coatings on aluminium alloys for thermal control system contain trivalent chromium or no chromium at all.

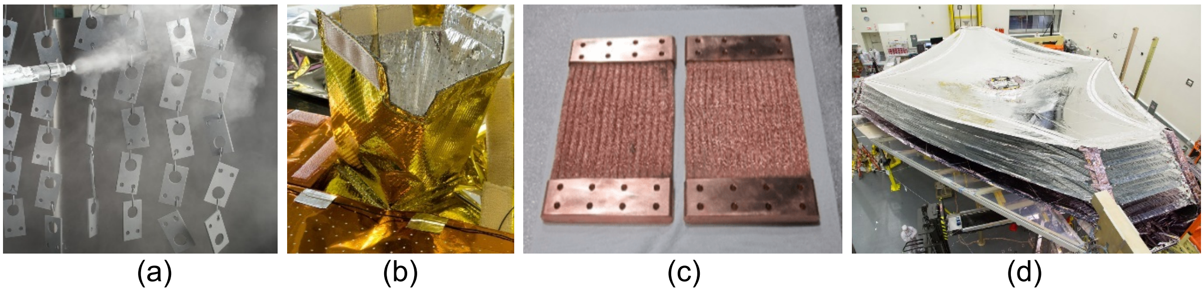


Figure 6. Pictures of passive thermal control systems. (a) surface coating; (b) MLI; (c) thermal strap; (d) sun shield.

2.2.3 Shielding and protection system

As hypervelocity impacts by meteoroids and orbital debris are a significant hazard for spacecraft, some spacecraft use the Whipple shield to protect payloads from the debris impact. The Whipple shield typically consists of the aluminium alloys 2219-T87 / 5456-H116 and aramid materials such as Nomex, Twaron, and Aracon.

In addition to impact shielding, spacecraft need to protect their payload from space radiation coming from galactic cosmic rays, trapped radiation, auroral radiation (polar orbits only), and solar flare. Several materials are commonly employed to shield against space radiation, which are including metals, polymers, and composite materials [3]. Metals, such as aluminium, copper, lead, and tungsten, are commonly used as shielding materials as they have high atomic numbers (Z) and densities, which can stop or deflect low-energy electrons and gamma rays. As polymers have high hydrogen content, which can stop or slow down protons and neutrons, polyethylene, polypropylene, and nylon are recently used as radiation shielding materials. Composites materials are also providing good radiation shielding as because the final product offers improved properties over its ingredients. Carbon fibre reinforced polymer (CFRP), boron nitride nanotube (BNNT), and graphene oxide (GO) are common composite material used to shield space radiation.

Some spacecraft have thermal protection system (TPS) to protect their payload from aerodynamic heating during atmospheric re-entry or to manage the heat shielding of propulsion devices. TPS materials are different from thermal control materials in that thermal control materials are used to moderate on-orbit temperatures, and TPS are generally for higher temperatures, such as around engine exhaust or for re-entry. Albeit there are reusable materials such as tiles or ceramic-matrix composites, ablative TPS materials are widely employed due to its simplicity and reliability [4]. An ablative TPS contains polymeric based ablators or uses graphite or carbon composite materials.

Table 2 lists common materials using in shielding systems including both metallic and non-metallic materials.

Table 2. List of materials commonly using in shielding systems

Category	Materials
Metal	aluminium alloy (2219-T87 / 5456-H116), copper, lead, tungsten

Non-metal	Nomex, Twaron, Aracon, carbon fibre reinforced polymer (CFRP), boron nitride nanotube (BNNT), graphene oxide (GO), silica-phenolic, carbon-phenolic, pyrolytic graphite (PG)

2.2.4 Payload

Optical systems are a common payload for remote sensing and Earth observation satellites. Quartz, fused silica, sapphire, magnesium fluoride, aluminium, silver, osmium are common materials found in optical systems including lens, mirrors, and solar reflector. Platinum, iridium, and nickel can also be used in optical coatings. Communication & RADAR satellites have large antennas which are using metals such as aluminium, titanium, and copper, as well as composites and ceramics.

Propulsion system

Propulsion systems can make up a large fraction of the total satellite mass and can be broadly classed into three major types: chemical, cold gas and electric. Chemical propulsion systems can then be subdivided into two classes: bi-propellant and monopropellant. The vast majority of these propulsion types and classes rely on the use of either liquid or pressurised gas tanks, commonly made from steel, titanium or aluminium-lithium and can have thicknesses in excess of several mm making them often the only equipment that survives atmospheric re-entry with multiple cases of recorded landfall of propulsion tanks.

The majority of propulsion systems also make use of valves, pipes and nozzles. These are often made from steel due to the need to withstand high pressures and exhaust temperatures. For chemical pi-propellant systems the nozzles can be made from high temperature alloys – typically niobium based such as C-103 – as the exhaust temperatures can exceed 2000K in many cases.

Electric propulsion systems can also make use of high conductivity and low wear materials in their anodes and cathodes such as tungsten.

List of materials commonly using in propulsion systems

Category	Materials
Tanks	Steel Alloys, titanium, aluminium-lithium
Valves & Piping	Steel Alloys
Chemical Thrusters	Steel Alloys, C-103
Electric Thrusters	Tungsten, Steel Alloys
Chemical Fuels & Pressurants	Hydrazine, IPA, Methanol, Liquid Oxygen, Nitrogen
Electric Fuels	Argon, Zenon, Krypton
Cold Gas Fuels	Nitrogen

2.2.5 Power system

As shown in Figure 7, solar arrays are most common primary power system in spacecraft, which consists of a supporting frame, a back board made from honeycomb sandwich materials, solar cells, and cover glass. Particularly, solar cells are made from the same kind of semiconductor materials as integrated circuits. Recent spacecraft use higher efficiency multi-junction solar cells having layers of germanium (Ge), gallium arsenide (GaAs), and gallium indium phosphide (GaInS). Since early the 2000s, the secondary power system of the satellite has been progressively shifted from MiMh to Lithium-ion batteries [5]. Lithium nickel cobalt aluminium oxide (NCA) and lithium cobalt oxide (LCO) are commonly used as a positive electrode in lithium-ion batteries. Negative electrode is commonly using graphite mixtures. The common chemical compositions of lithium cells are lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide (LMO), lithium sulfur (LiS), and lithium iron phosphate ($LiFePO_4$) [6]. Table 3 summarises the list of common materials using in satellite power systems.

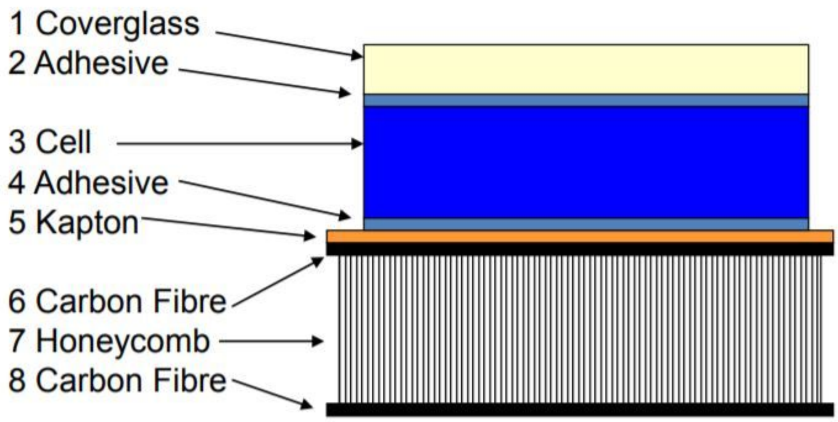


Figure 7. A schematic of a solar array [7].

Table 3. List of materials commonly using in power systems

Components	Materials
Frame	aluminium alloy
Back board	aluminium, composite materials
Cover layer	silicon dioxide
Solar cell	silicon, Ge, GaAs, GaInS, NCA, LCO, $LiCoO_2$, LMO, LiS, $LiFePO_4$

2.2.6 Other systems: Lubricant, Seal and Adhesive

Liquid and solid lubricants used in spacecraft for moving mechanical assemblies. Some commonly used liquid lubricants include perfluoropolyethers (PFPE's), multiple alkylated cyclopentane (MAC), and polyalphaolefins (PAO's). Solid lubricants include molybdenum disulfide, tungsten disulfide, niobium diselenide, graphite powder, silver, Teflon (polytetrafluoroethylene), and nylon. A resin binder or inorganic binder is used for bonded solid lubricants. The molybdenum disulfide lubricants are commonly used in sliding components such as a solar array rotary joint.

Seals are used to maintain spacecraft pressurization, pneumatics, and hydraulics, which are made of metal or elastomer. Metal seals can be made of soft aluminium, copper, or stainless steel, though nickel, Monel, and Inconel have been used in the past. A wide variety of elastomeric seal materials are available, including butyl rubber, silicone, Viton, Teflon, Kel-F fluoropolymer, and Neoprene.

Spacecraft uses two classes of adhesives, which are structural adhesives, such as those used in honeycomb laminate manufacture, and non-structural adhesives, such as the pressure sensitive adhesive used for thermal control tapes. Cytec FM-300 and 3M AF-191 film adhesives have been commonly used for honeycomb core/face bonds, Hysol EA9394 paste for external splices. Pressure-sensitive adhesives are usually either acrylic or silicone-based, such as 3M 966, 3M 9406PC, 3M 9703, Arclad 8026, NuSil CV-1144, and DC93-500. Other adhesive materials include polyurethanes, cyanoacrylates, and polyimides.

The list of materials using in lubricants, seals, and adhesives are summarised in Table 4. As can be seen, wide ranges of polymers are presented.

Table 4. List of materials commonly using in lubricant, seal and adhesive

Application	Materials
Lubricant	perfluoropolyether (PFPE), multiple alkylated cyclopentane (MAC), polyalphaolefin (PAO), molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), niobium diselenide ($NbSe_2$), graphite, silver, Teflon (polytetrafluoroethylene), nylon
Seal	aluminium, copper, stainless steel, nickel, Monel, Inconel, butyl rubber, silicone, Viton, Teflon, Kel-F fluoropolymer, Neoprene
Adhesive	acryl, polyester, thixotropic, polypropylene, RTV silicone, polysulfidr, polyurethanes, cyanoacrylates, polyimides

2.3 Biproducts of Atmospheric Ablation

Space debris re-entry, whether from spacecraft or rocket parts, triggers the formation of various chemical by-products. This phenomenon results from the interaction between the debris' original composition and the upper atmosphere. The debris' initial kinetic energy is converted into heat, causing a surge in surface temperature, which promotes the oxidation of the debris' complex components. By understanding the pressure and temperature conditions generated during atmospheric re-entry, the most chemically stable by-products can be predicted and quantified using Gibbs Energy Minimisation (GEM) method. GEM is to determine the chemical composition of a complex mixture in a closed system (like the re-entering debris) at a given pressure and temperature by minimising the Gibbs free energy of all possible chemical species.

The minimisation of the Gibbs free energy is related to atomic molecular balance as:

$$\boldsymbol{minG(P,T,n)} = \sum_N \boldsymbol{n_i} \cdot \boldsymbol{\mu_i(P,T,n)} \tag{4}$$

where $\boldsymbol{n_i}$ is mole number of component i, N is number of species, and $\boldsymbol{\mu_i}$ is the chemical potential of component i. As the atmosphere pressure is low enough during the atmospheric re-entry, we can assume ideal conditions for the gas phase. Therefore, the chemical potential for the gas and the condensed species produced during the material ablation can be expressed as:

$$\boldsymbol{\mu_i(T, N_c) = \mu_i^0(T)} \quad (5)$$

$$\boldsymbol{\mu_j(P, T, N_g) = \mu_j^0(T) + R \cdot T \cdot \ln\left(\frac{n_j}{\sum_{N_g} n_j}\right) + R \cdot T \cdot \ln\left(\frac{P}{P^0}\right)} \quad (6)$$

where $\boldsymbol{\mu_i^0(T)}$ is the standard chemical potential, and $\boldsymbol{P^0}$ is the pressure of reference at ground level.

The possible chemical by-products generated during ablation are ultimately limited by the elemental composition of the ablated material. In addition to the ablated material's atoms, oxygen and nitrogen from the surrounding atmosphere must be considered, as they readily react with the spacecraft at high re-entry temperatures. Each potential by-product possesses a unique standard chemical potential, and the final chemical composition of the system is dictated by a combination of factors which are temperature, pressure, and these individual chemical potentials.

Two prominent thermochemical databases, NASA [8] and Burcat's [9], offer resources for analysing these reactions. The primary distinction between these databases lies in the number of chemical species considered and the level of internal thermodynamic data consistency. While the level of self-consistency doesn't significantly impact the final by-product ratios, the choice of database becomes more relevant based on the number of possible substances included. Using GEM approach, expecting byproducts from the ablation of AA7075-T6 aluminium alloy, which is one of widely used structural materials in space and satellite technologies [10], are identified in Table 5.

Table 5 Identified biproduct species from the ablation of aluminium alloy [11]

Phase	Species
Gas	Al, AlN, AlO, AlO_2, Al_2, Al_2O, Al_2O_2, Al_2O_3, Cr, CrN, CrO, CrO_2, CrO_3, Cu, CuO, Cu_2, Mg, MgN, MgO, Mg_2, N, NO, NO_2, NOO, N_2O_2, NO_3, N_2, N_2O, N_2O_3, N_2O_4, N_2O_5, N_3, O, O_2, O_3, Zn, CrO, CuO, Cu_2, N_4, O^*, O_2^*, O_3, O_4, ZnO
Condensed	Al (cr), Al (liq), AlN (cr), AlN (liq), Al_2O_3 (a), Al_2O_3 (liq), Cr (cr-a), Cr (cr-b), Cr (liq), CrN (cr), Cr_2N (cr), Cr_2O_3 (I′), Cr_2O_3 (I), Cr_2O_3 (I), Cr_2O_3 (I), Cr_2O_3 (liq), Cu (cr), Cu (liq), CuO (cr), Cu_2O (cr), Cu_2O (liq), Mg (cr), Mg (liq), $MgAl_2O_4$ (cr), $MgAl_2O_4$ (liq), MgO (cr), MgO(liq), Mg_3N_2 (cr), Zn (cr), Zn (liq), ZnO
Ions	Al^+, Al^-, AlO^+, AlO^-, AlO_2^-, Al_2O^+, $Al_2O_2^+$, Cr^+, Cr^-, CrO_3^-, Cu^+, Cu^-, Mg^+, N^+, N^-, NO^+, NO_2^-, NO_3^-, N_2^+, N_2^-, N_2O^+, O^+, O^-, O_2^+, O_2^-, Zn^+, CrO_3^-, NO^-, NO_2^+, NO_2^-, NOO^+, NOO^-, NO_3^+, NO_3^-, N_2^-, N_2O^+, N_2O^-, N_2O^+, $N_2O_3^+$, $N_2O_3^-$, N_3^+, N_3^-, N_4^-, O_3^+, O_3^-, O_4^+, O_4^-

For titanium alloy such as Ti-6AL-4V, consisting of Ti 90%, V 4% and Al 6% in weight, expecting by-product are TiO_2, TiO, Al_2O_3, AlO, VO_2, VO, V_4O_{10}, NO, NO_2, N_2O, O_3, O, and N.

Due to their high melting point, their metallic oxide production covers wide range altitude including lower altitudes upto 35 km.

Figure 8 shows the categorised four primary by-products from the atmospheric ablation of spacecraft. Modern small LEO spacecraft are predominantly composed of metals (approximately 25%), plastics (20%), and electronic components (55%) [12]. When these spacecraft re-enter the atmosphere, they undergo ablation, generating various by-products. These by-products include metal nanoparticles and metal oxides, such as alumina (Al_2O_3) and aluminates ($MgAl_2O_4$), formed from the oxidation of the satellite's metallic components.

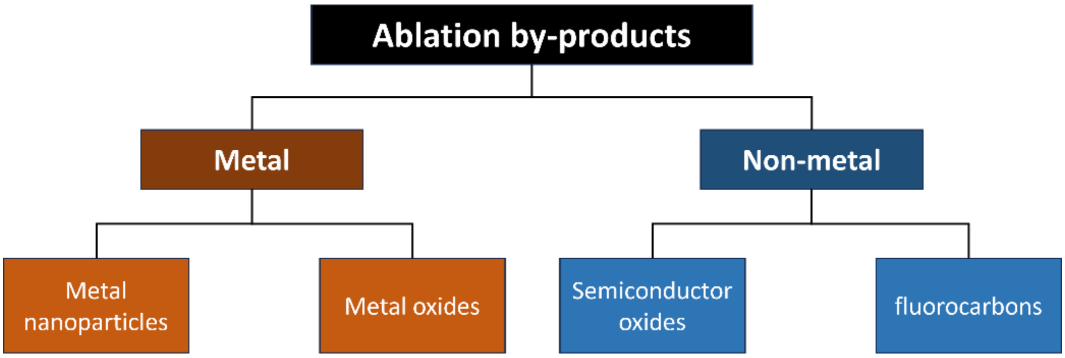


Figure 8. Categorised by-products from the atmospheric ablation of spacecraft.

The formation of these by-products is influenced by the intense heat generated during re-entry, which facilitates chemical reactions between the satellite material and the surrounding atmosphere. Notably, the resulting metal atoms readily oxidize below 85 km altitude, leading to the formation of nanoparticles and metal oxide compounds. The distribution of these by-products is uneven, with a concentration in polar regions. This phenomenon is attributed to global atmospheric circulation patterns, which bring descending air from the mesosphere into the stratosphere during winter.

Approximately 30 tons of cosmic dust enter Earth's atmosphere daily, contributing roughly 150 tons of aluminium annually (approximately 1.4% of the total mass) [13]. Remarkably, human activity has nearly matched this natural influx of aluminium, with anthropogenic sources injecting a comparable amount into the atmosphere in 2021. The growing number of LEO satellites has further exacerbated the situation, with the total mass of re-entering objects increasing by 21% to 332.5 metric tons in 2022 [14]. This growing trend raises concerns about the potential impact of these by-products on the stratosphere. Studies indicate that nitrogen oxides and chlorine, by-products of re-entry, can contribute to long-term ozone depletion, particularly in the Antarctic [15]. Furthermore, the influx of metal nanoparticles from satellite ablation may interact with existing stratospheric sulfuric acid particles, potentially altering their properties and distribution.

Both metal and non-metal by-product of spacecraft ablation can bring known and unknown impacts into environments, including ozone layer depletion and global climate change by altering solar radiation reflection and scattering. Table 6 summarises the known and unknown impacts of atmospheric ablation. In addition to the ozone layer depletion, metal oxides can influence the Earth's climate in two ways. First, they can reflect incoming sunlight back to outer space which is the direct effect. Secondly, the metal oxide particles block part of the energy that would have reached the surface, thus having a cool effect on the climate.

Table 6 Summary of the potential and expected impacts of spacecraft ablation. Expected impacts have been identified by previous scientific studies, while potential impacts refer to environmental effects that have not yet been scientifically confirmed but are highly likely to occur.

Expected impact	• Ozone layer depletion by metal oxides. • Increasing the reflection and scattering of Solar radiation (Earth's albedo).
Potential impact	• Magnetosphere perturbation as metallic particles can block, distort or shield of magnetic fields. • Increasing thunderstorm in stratosphere by affecting the conductivity of atmosphere. • Disturbing satellite communications. • Accuracy of satellite remote sensing by affecting the atmospheric refractive index. • Long-term environmental effect. • Global public health outcomes related to hydrologic cycling, atmospheric chemical cycling, frequency of natural disasters, food system disruptions, and ecological health through the pathways of water, air, soil, and biota. • Atmospheric turbulence

3 Space Activities

The purpose of this section is to provide an estimate of the anticipated amount of ablating materials expected to be released from current and planned space activities. As this is predicting the future several assumptions must be made clear:

1. A window of the next decade is considered (2024-2034), beyond this is not sensibly predictable.
2. That only a fraction of the currently proposed mega-constellations will be successful in launching the majority of their planned satellites. These projects are extremely resource intensive ($10+Bn endeavours) and the majority will not achieve their funding goals due to the size of the current investment pool.
3. No significant conflict will be carried out in space, such an event would likely lead to a significant increase in atmospheric ablating debris as fragments generally re-enter deorbit passively much faster than their parent spacecraft.
4. That the 25 year deorbit rule will be maintained and that newer satellites will shift to the FAA's proposed 5 year rule, leading to an increase in the number of end-of-life de-orbit manoeuvres and deployable re-entry sails/tethers.

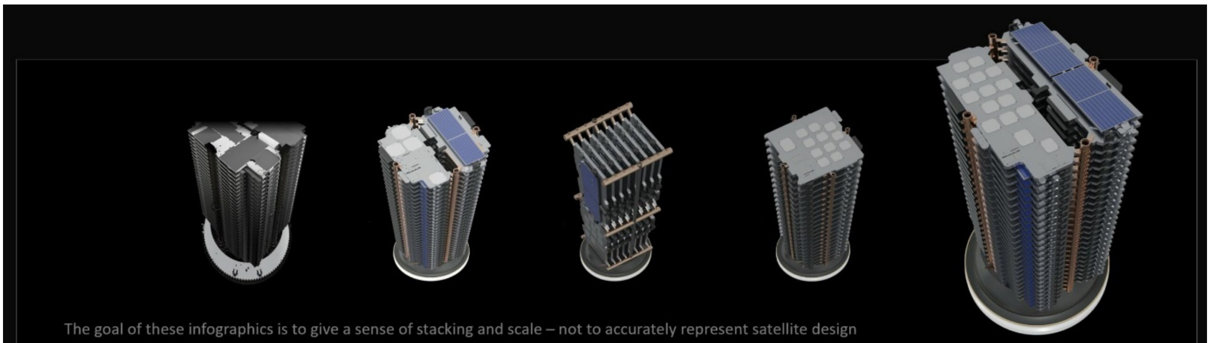
3.1 Current Activities

The primary statistical information source on current activities used in the following sections is from the Union of Concerned Scientists (UCS) who publish a comprehensive analysis of existing satellites which was last updated in May 2023 [16]. At this point there were 7,560 operational satellites and over the previous five years the number of operational satellites had grown on average by 39%. Five major categories are defined by the UCS and used in this section; communications, Earth Observation (EO), Earth Science, Navigation, Space Science and Technology Development. Together these represent 98.6% of all launches.

In 2023 communications satellites made up 73% of all active satellites and are primarily situated in Geostationary Orbit (GEO) and Low Earth Orbit (LEO), however there are some in highly elliptical Medium Earth Orbits known as Molniya Orbits. The majority of communication satellites are in LEO and configured in shells of constellations that provide global coverage, with the biggest owners being Starlink (6,350 satellites as of writing), OneWeb (648), Iridium (80) and Globalstar (52) respectively. As Starlink and OneWeb present the bulk of communication satellites in orbit they are discussed in more detail in the following sections.

3.1.1 Starlink

Starlink has the ambition to become a major global broadband internet and direct to cell phone provider by deploying thousands of "Starlink" satellites with both Earth to Space links and inter-satellite links. The Starlinks have gone through multiple generations since the launch of the first "Tintin" test satellites in 2018 with representatives of the V1.0, V1.5 and V2.0 Mini generations still in orbit. To date 4,714 V1&V1.5 Starlinks have been launched and 522 have already de-orbited [17]. 2224 of the V2 Mini's have been launched and 598 have already de-orbited. The larger V2's are planned once SpaceX's Super Heavy Lift Starship has been brought into active service, but the author cannot speculate as to when that may be – but it is likely that V2's will become the dominant Starlink variant in the constellation over the next decade. Starlink have not released publicly significant amounts of data related to the Starlinks, but 3rd party informed speculation of the relative generations after V1.5 is shown in Figure 9.



Designation	Starlink V1.5	Starlink V2 F9-1	Starlink V2 F9-2	Starlink V2 mini	Starlink V2 Starship
Status	Launched	FCC filing – may not realize	FCC filing – may not realize	Launched	FCC filing
Mass kg	306	303	800	800	2000
Gbps / sat	15	18	70	60	170
Launch	60 units per Falcon 9	60 units per Falcon 9	16 units per Falcon 9	21 units per Falcon 9	50 units per Starship
Tbps / launch	0.9	1.1	1.1	1.3	8.5
m$ / launch	Sats 18 + launch 30 = 48m$	Sats 18 + launch 30 = 48m$	Sats 11 + launch 30 = 41m$	Sats 15 + launch 30 = 45m$	Sats 60 + launch 15 = 75m$
$ / Mbps	53	45	37	35	9
Direct-to-mobile?	No	No?	Yes	Yes?	Yes

Assumptions

This is not investment advice (just some assumptions)

8

Figure 9. 3rd Party Comparison of the Starlink satellite generations [18]

The Starlinks have a unique design when compared to other satellites, including other communications ones. They have been optimised for maximum volume utilisation inside a launcher fairing which has led to a flat design, with a single large deployable solar array and a zenith face with multiple flat phased array antennae. They have electrical thrusters which enable orbit raising post launch, orbit phasing, collision avoidance and orbit lowering for disposal. Space Forge have carried out an internal analysis of the design constraints of the V1.5 Starlink in order to draw conclusions about the art of the possible for its high power manufacturing satellites and have concludes that:

- The 30 m^2 solar array generates approximately 7 kW of power when in sunlight and approximately 5.4 kW orbit average power
- That at least 11 kg of Lithium batteries are required to maintain a steady delivery of generated power whilst in eclipse
- That the top and bottom surface area is sufficient to keep the Starlink at a < 20℃ average temperature without the need for additional deployable radiators
- That the primary structure of the Starlink is likely made from a high thermal conductivity alloy of aluminium in order to distribute the heat to keep the radiation efficient, potentially Aluminium-Lithium.

In order to provide global overlapping coverage, the Starlinks are arranged in over several orbital shells at slightly different altitudes to reduce the potential for collisions, as shown in Table 7

Table 7. List of Starlink Active Orbital Shells [17]

Shell	Altitude [km]	Inclination [°]	Planes
G1 Group 1	547	53	72
G1 Group 2	572	70	36
G1 Group 3	560	97.6	6
G1 Group 4	547	53	72
G2A Group 6	559	43	28
G2A Group 7	547	53	72

Previous analysis carried out by Space Forge into the rate of large object (Radar cross section > 1 m^2) re-entry over the 1st quarter of 2024 showed that 40% of all re-entries are a Starlink, at a rate of approximately 11 a week. Assuming the bulk of these are the aging V1.5s this currently represents an ablation mass into Earth's atmosphere of ~500kg/day.

It is not clear if Starlink are carrying out controlled re-entries and how much of the de-orbit velocity is provided by the electrical thruster and how much via the drag of the solar panel, however for the purposes of this project addressing ablation of materials in Starlink should be a high priority.

3.1.2 OneWeb

OneWeb (a joint venture between AirBus and OneWeb) is providing internet backhaul which to date has launched 640 satellites of which only 6 have re-entered [60]. They are arranged into 24 planes in a single shell at 1,200km at 87.9° inclination [60].

Based upon Space Forge's internal analysis the OneWeb satellites have:

- 150kg launch mass
- 1.3 m^2 solar array generating 700 W peak power and 546 W orbit average power
- Xenon hall effect thrusters with sufficient fuel to carry out enable orbit raising post launch, orbit phasing, collision avoidance and orbit perigee lowering for disposal.
- The ratio of internally dissipated heat to radiation area makes the satellite relatively cold and so no special radiators or structural materials are required – therefore they are likely built from aluminium 2000 series alloy panels.

The deorbit procedure of OneWeb satellites has not been publically documented, however they are expected to be compatible with the 25 years deorbit rule which from a 1,200 km orbit would require a significant perigee lowering burn (likely to < 500 km) to accomplish.

They are reported to re-enter within 25 years of retirement.

3.1.3 Summary

Re-Entry relevant statistics based upon the six major classes of satellite have been compiled using the UCS data [59] and given in Table 8. The number of re-entries is based upon the average lifetime and the assumption that the satellites are deorbited soon after the end of that lifetime.

Table 8. Summary of re-entry relevant data for different satellite classes

Purpose	Average Mass (kg)	Average Operational Lifetime (years)	Median Perigee (km)	YoY population Growth*	Number launched per year*	Est. Re-entries per year in 2023
Communications	590	5.31	548	57%	841	74
Earth Observation	809	4.80	524	22%	136	26
Earth Science	299	3.43	500	29%	4	2
Navigation	1,576	9.44	21,491	9%	10	0**
Space Science	981	4.44	552	12%	80	5
Technology Development	182	2.88	524	25%	54	28
Totals / Averages	**626**	**5.35**	**536**	**39%**	**1,053**	**135**

**5 year averaged annual growth (2018-2022)*

***Navigation satellites are moved into graveyard orbits instead of being de-orbited.*

Table 8 shows that the strongest growth and current majority of re-entries are coming from communications satellites, representing an average of 44 tons of re-entering material per year. Earth Observation and Technology development are the next largest contributors, but their level of growth is not as high and so they are expected to be outstripped by communications in the near future.

3.2 Future Trends

Total Year on Year (YoY) growth in satellites launched in orbit averaged over the last 5 years is 39%, over 10 years averaged 27% and over 20 years averaged 22%. The increase in satellite growth rate over the last decade is likely attributed to the growth in satellite constellations, particularly the mega-constellations of OneWeb and Starlink which alone represent over half of all active satellites in orbit. If this mega-constellation driven growth rate of the last five years' rate of growth continues for the next decade, then the number of active satellites in orbit could reach 43,000 by 2034. However, if the mega-constellation business models are not proved to be successful, it is likely that satellite growth over the next decade would be more similar to the previous decade (at 27%) which would still result in a significant increase to around 17,000 satellites.

There are several constellations currently in development that could make this growth level a realty (and potentially exceed it) including:

- Starlink Gen 2 (US, 39396 sat)
- Kuiper (US, 3232)
- Guo Wang (China, total: 12992 satellites)
- Astra (US, 13620 satellites)
- Semaphore-C (EU, 116640 satellites)
- E-Space (France, 300,000 satellites)

However, none of these mega-constellations are yet fully funded and the most advanced, Starlink, is only 10% of the way to achieving these proposed constellations sizes.

A growth of between 27-39% in satellites would come with a significant increase in the number of annual re-entries over the next decade, however the rate is offset by the lifetime of the satellites, with the bulk being communication satellites that have an average lifetime of around 5 years. Rough predictions for the growth in number of re-entries and total mass between 2023 and 2033 can be seen in the table below:

Table 9. Comparison between estimated re-entries per year in 2023 and 2033

	2023		2033	
Purpose	**Re-entries per year**	**Re-entry Mass per year [tons]**	**Re-entries per year**	**Re-entry mass per year [tons]**
Communications	74	44	5,561	3,281
Earth Observation	26	21	166	98
Earth Science	2	0.6	24	14
Navigation	0*	0*	0*	0*
Space Science	5	5	16	9
Technology Development	28	5	322	190
Totals / Averages	**135**	**76**	**6,089**	**3,592**

**Navigation satellites are moved into graveyard orbits instead of being de-orbited.*

These estimates show a potential 3,592Tn of mass re-entering every year by 2033, a 47x increase over 2023. For perspective it is estimated that around 16,000Tn of meteor material (usually in grain form) hits Earth's atmosphere every year [18], [19] – a mass flux that could well be exceed by re-entering satellites in the 2030s, with potentially disastrous atmospheric consequences.

4 Challenge and Barriers

4.1 Scientific Challenges

Recent measurements indicate that approximately 10% of aerosol particles in the atmosphere contain aluminium and other metals originating from spacecraft re-entry [20]. As addressed in the previous section, we are projected to see a global increase in emissions from thousands of spacecraft launches and re-entry events in the coming decades. Currently, nearly 10,000 active LEO spacecraft are in orbit, with over 100,000 additional LEO spacecraft proposed. The common post-mission disposal strategy for LEO spacecraft and debris is to ensure their re-entry into Earth's atmosphere, where they ablate and burn up. Since the spacecraft materials are mainly injected at mesospheric heights, potential influences on mesospheric and even stratospheric chemistry, such as effects on the ozone layer, cloud formation, or climate, are conceivable. However, the impact of this sustained and elevated level of metallic and non-metallic content on the properties of stratospheric aerosols remains unknown, and there are only limited studies on the atmospheric effects of propellants. This leads to yet further scientific and engineering challenges that need to be addressed to prevent and minimise the harmful environmental impact of disposing spacecraft and debris through atmospheric re-entry.

4.1.1 Modelling and Prediction

Predicting re-entry flow and material ablation requires extensive understanding complex physical phenomena involving thermo-chemical non-equilibrium flows and material responses to hot plasma experienced during atmospheric entry. Atmospheric re-entry flow analysis is a critical component to model and predict the ablation of spacecraft materials entering atmosphere it requires accurate prediction of surface properties such as heat flux, pressure and shear stress. When spacecraft re-enters though an atmosphere, it will experience three different flow regimes, continuum, transition, and rarefied flows, due to the variation of atmospheric density with altitude. Involving three different flow regimes **impose computational challenges as each flow regime requires different simulation techniques**. The flow regimes categorise using Knudsen number defining the ratio of the molecular mean free path length to a representative physical length scale as:

$$Kn = \frac{\lambda}{L} \tag{7}$$

where λ is a mean free path and L is a representative physical length.

In the continuum regime, characterized by very low Knudsen numbers, flows around spacecraft entering atmosphere can be accurately simulated using traditional Computational Fluid Dynamics (CFD) by solving the Navier-Stokes (NS) equations. The NS equations can be derived from kinetic theory based on the assumption of a small perturbation from an equilibrium velocity distribution function and linearly varying transport properties. Conventional CFD methods also assume that the flow remains in thermodynamic equilibrium meaning the internal energies such as rotational, vibrational and electronic energies remain in equilibrium with the translational energy. In areas of the flow having large gradients such as the shock and boundary layers near the wall, these assumptions of equilibrium break down.

In the rarefied flow, the re-entry flow can be simulated using the direct simulation Monte Carlo (DSMC) method. The DSMC method does not depend on assumptions involving a small perturbation from equilibrium and hence is more accurate than CFD methods for non-equilibrium flows. However, the DSMC method is computationally about an order of magnitude expensive than CFD. Even the re-entry flow is in continuum regimes, it could locally in a rarefied regime when if the local characteristic length scale is very small. For example, a high-density fore-body flow on a spacecraft having blunt nose can create a rarefied flow in the wake of the vehicle. While the DSMC method can be applied to all flow regimes in principle, it becomes prohibitively expensive for Knudsen numbers less than 0.001. Therefore, affordable computational method is required to investigate the effect of material ablation across various atmospheric altitudes.

In addition to computational challenge, atmospheric re-entry flows have **challenges in physical modelling for high-fidelity simulation** due to the thermo-chemical non-equilibrium. The thermo-chemical non-equilibrium effect is still one of the vital problems for the accurate prediction of re-entry spacecraft. As it is quite difficult to reveal the complex fluid mechanisms in ground test facilities and flight data are too expensive to obtain plentifully, numerical simulation has become an effective approach to simulate these atmospheric re-entry flow. While a variety of CFD solvers, including Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA), Data Parallel Line Relaxation (DPLR), LeMANS (University of Michigan Aerothermodynamic Navier-Stokes Solver) and US3D have been developed to solve the well-known Navier-Stokes equations coupled with chemical kinetic models or thermos-chemical non-equilibrium model, much effort has been brought into the development and validation of different thermal and chemical models proposed by Blottner [21], Park [22], [23] and Gupta [24]. Different models may yield significant differences in the thermos-chemical non-equilibrium processes and distributions of the gas species.

4.1.2 Experiment and Verification

Ground test of material ablation during atmospheric entry/re-entry requires high-enthalpy facility which can maintain the flow longer than few seconds. Albeit a shock tube/tunnel can generate high-enthalpy flows, it cannot maintain the high-enthalpy flow long enough for ablation test. Among all the ground test facilities that have been developed since 1970s for testing material ablation during atmospheric re-entry, arc jet ranks as the most flight relevant and extensively used test facility in the history of material ablation research, and continue to play, a critical role not only in the development of ablative TPS materials, but more importantly, in the flight vehicle integrated development and in the flight qualification.

An arc jet is a high-temperature plasma wind tunnel where an electric arc, anchored between an anode and a cathode, heats the high pressure and nearly stagnant gas to a high-temperature, high pressure plasma. The heated gas in an arc heater is then expanded through a convergent-divergent nozzle to supersonic or hypersonic jet. As shown in Figure 10, the conditions generated behind the shock wave on the test article are similar to re-entry conditions on a spacecraft when a small test article is introduced into the jet. By varying the electrical power and the mass flow rate, the energy density (or enthalpy) of the gas stream and the surface heat flux and the pressure on the test article can be varied for performing test to match required flight like conditions.

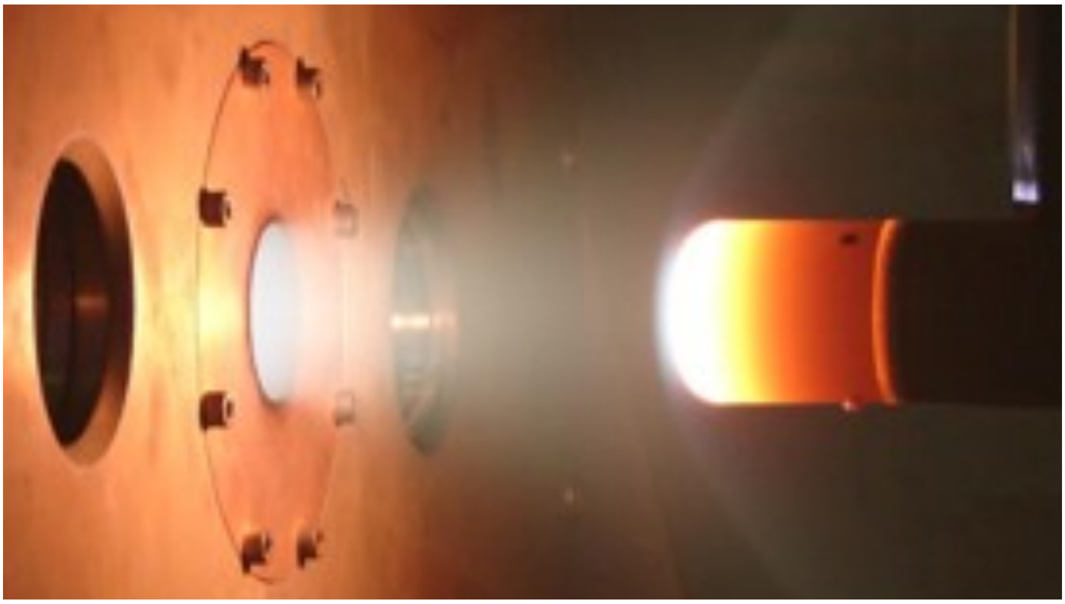


Figure 10. Testing material ablation during atmospheric re-entry using an arc-heated plasma wind tunnel (L2K) in DLR, Cologne.

Arc heaters are key components of arc-heated plasma wind tunnels, also known as arc jet wind tunnels, which consist of three fundamental elements: a discharge container, electrodes, and a nozzle. The desired test gas is injected into the arc discharge container section, where an arc discharge passes between the electrodes, heating the gas to a high temperature. The generated plasma then flows through a converging/diverging supersonic nozzle, producing a simulated atmospheric-entry heating environment. Consequently, the electrodes are in direct contact with the generated plasma flows. Due to arc discharges, the electrodes experience material erosion, resulting in the presence of material particles from the eroded electrodes in the plasma flows. Although these metallic particles do not significantly affect the ablation rate of a sample specimen, they can influence the chemistry related to the by-products of material ablation. Therefore, **current arc-heated plasma wind tunnel facilities are not suitable for identifying the by-products of spacecraft ablation during atmospheric re-entry**.

Inductively heated plasma wind tunnels are another type of ground test facility used to simulate atmospheric re-entry flows for material ablation. The Plasmatron at VKI is a high enthalpy facility that uses an inductively coupled plasma heater. In this facility, the test gas is heated by inductive coupling between the inductor and the gas, resulting in a plasma flow free from metal contamination. While it can simulate a clean re-entry flow in terms of temperature, the **generated flow is subsonic and therefore cannot replicate the kinetic energy of a re-entry flow**.

Furthermore, current ground test facilities, including both arc-heated and inductively coupled plasma wind tunnels, are designed to generate atmospheric entry/re-entry flows at specific conditions. Since producing different flow conditions requires changing the converging/diverging supersonic/hypersonic nozzle, **it is challenging to dynamically simulate the entire re-entry trajectory.** This limitation is crucial for investigating the environmental impact of spacecraft ablation across various altitudes.

In addition to the technical challenges related to testing capability, data sharing and testing protocols are imposing other challenges in the experiments of material ablation. Due to the nature of re-entry material ablation, testing facilities and measured data are open in the export control. As experiment facilities and measurement techniques related to atmospheric re-entry ablation are often referred to as 'dual-use', it is challenging to access non-UK test facilities and exchange atmospheric ablation data internationally. Due to the unique characteristics of each ground test facilities, **there is no standardised protocols for testing and verifying material ablation** during atmospheric re-entry, such as sample size, exposure time, flow conditions, and measuring parameters.

4.1.3 Long-term Environmental Impact

While it is widely accepted that most re-entering spacecraft and debris will burn up during re-entry, the effects of their byproducts on Earth's atmosphere have only been lightly studied, leaving the long-term impact largely unknown. These byproducts could have significant consequences, particularly for the ozone layer. The environmental impacts from satellite re-entry remain poorly understood, although it is known that aluminium oxides generated by spacecraft ablation during re-entry could accelerate ozone depletion. Key questions we need to address to understand the environmental impact of spacecraft re-entry on the atmosphere include:

- What is the allowable annual mass of atmospheric ablation from spacecraft and debris?
- What are the long-term atmospheric changes caused by spacecraft and debris ablation?
- How long do ablated byproducts remain in the upper atmosphere?
- What are the long-term environmental impacts of atmospheric ablation, including effects on climate change, ozone depletion, resource depletion, toxicity, and biodiversity?
- How does the sustained and increased level of metallic content influence the properties of stratospheric aerosols?
- How does the impact / amount of materials compare to that resulting from other industry sectors

4.2 Regulatory Challenges

The framework of laws (both international and domestic), regulations, institutions and practices which govern the space and environmental domains is complex and multi-layered. **Atmospheric ablation of re-entering space objects does not fit cleanly or clearly within existing regulatory frameworks, leading to several challenges**.

Broadly speaking [space] governance can be "… defined as principles, norms, rules and decision-making procedures around which [space] actor expectations converge in a given issue area." [25]. The space governance framework is made of both binding and non-binding instruments and tools, including: international treaties, principles, technical guidelines, standards and national regulation, which are complemented with industry best practices Within the existing space governance system, no binding law or regulation directly addresses or imposes requirements relating to atmospheric ablation of re-entering space objects, while only a limited number of non-binding instruments address the issue. Space governance frameworks do, however, include many provisions, both binding and non-binding, relating to space debris mitigation, including requirements to dispose of space assets at end-of-life. These requirements generally focus on the safety of space operations and sustainability of the space environment; and/or safety of uninvolved third parties; and do not address the impact on the human or terrestrial environment. Other areas of space governance and regulation address the environmental impacts of launch or spaceport activities, generally through domestic/national requirements for environmental impact assessments (EIAs). However atmospheric ablation of re-entering space objects is generally not explicitly covered by these EIAs.

4.2.1 Space Policy Limitations on Atmospheric Ablation: International and Domestic

The environmental consequences of atmospheric ablation have not been highlighted as a priority within international space policy. Instead, the state of international policy on space activities has focused on the sustainability of space activities at the forefront of discussions. Although related, the concept of sustainability has been interpreted as applying pre-dominantly to the avoidance of orbital congestion and promotion of debris mitigation and remediation (including active debris removal (ADR)) techniques. This consensus has been reached by several institutions ranging from the World Economic Forum in their Space Industry Debris Mitigation Recommendations (SIDMR) [26], the Inter-Agency space Debris Coordination Committee space debris mitigation guidelines [27], the European Space Agency's (ESA) Zero Debris Charter [28], and the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Guidelines for the Long-term Sustainability of Outer Space activities (LTS Guidelines) [29] and Space Debris Mitigation Guidelines [30].

Where post-mission disposal mechanisms[1] are mentioned, they provide little to no specific recommendations or actions to ensure the impact of atmospheric ablation is minimized[2]. The exception lies in ESA's Zero Debris Charter which outlines the need to recognize the impact of space debris re-entry.[3] However, it similarly gives no strong indication or call for action on the issue of atmospheric ablation at hand, partly because it is an aspirational document that is still in the early stages of developing implementation guidance. Furthermore, to the detriment of atmospheric ablation, non-binding and voluntary guidelines have recommended the reduction of the standard orbital lifetime of spacecraft[4], particularly in LEO. Instead of applying the standard orbital lifetime of 25 years or shorter after end of life[5], the issue of orbital

1 Space mission operational phase concerning the use of space objects at the end of their mission and after performing actions to reduce hazards to spacecraft and orbital stages in space.

2 See guideline 5 of the Space Debris Guidelines n3, see solution point 1 of the SIDMR n1, and Guideline D.2 n5 of the LST Guidelines n4

3 See IADC footnote n3, paragraph 1.

4 See solution point 1 of the SIDMR n1 "All spacecraft operators should strive for a target of five years or below after end of life for removal of spacecraft"

5 See section 5.3.2 of the IADC guidelines n2, and NASA (2024). State-of-the-art of small spacecraft technology. Retrieved from https://www.nasa.gov/smallsat-institute/sst-soa/deorbit-systems/

congestion and increased launches has prompted the need to reduce this time to 5 years[6], bringing back countless pieces of debris at an earlier time. Although this change of policy addresses the pressing issue of debris proliferation in space, it consequently introduces more objects back into Earth's atmosphere.

Beyond the trend of introducing measures to encourage space objects to re-enter sooner, ADR techniques have become more popularized. Among others, Japan and the UK have dedicated national missions and inter-state collaboration towards this. Commitments by the UK Space Agency, following the National Space Strategy of the UK government, have directed £102 million towards delivering studies on tracking space objects and reducing debris [31]. Following this, UK-based companies: Astroscale and ClearSpace, were awarded £4 million to design missions that supported the removal of space debris with further funding on the horizon to support the launch of the UK's first national space debris removal mission in 2026 [31]. According to the Workforce Foresighting Hub's report (2024), training standards related to the workforce in the ADR sector need to expand and be updated to meet the UK's debris removal and space exploration objectives [32].

4.2.2 Fragmentation of regimes

International legal fragmentation is a long-observed phenomenon that demonstrates the independent development of separate legal approaches, norms and institutions in response to specific functional issues, which enter into collision as regulation expands [33]. In Public International Law, the Outer Space Treaties regime and the Ozone Treaty regime develop specialised norms and institutions intended to govern distinct, yet overlapping Areas Beyond National Jurisdiction (ABNJs): Space and the Atmosphere. Most international treaties and documents do not define the boundaries of either "space" or the "atmosphere", even though they are the object of protection for the purpose of the application of those treaties. Whereas the exploration and use of outer space is "the province of all [hu]mankind[7]", atmospheric pollution and atmospheric degradation are a "common concern of humankind."[8]

As a result of international legal fragmentation, two Areas Beyond National Jurisdiction (ABNJs) are governed by separate legal regimes. International space law is connected to the broader body of international law through Article III of the Outer Space Treaty (OST). General principles, such as treaty interpretation and concepts of state responsibility, are consistent with those applied across international law[9]. However, Earth and space are interconnected systems, where activities in one protected area can create risks for the other. For example, efforts to reduce space congestion, such as the end-of-life disposal of satellites by

[6] See SIPDMR (n27) and Federal Communications Commission (FCC) (2022). FCC adopts new '5-year rule' for deorbiting satellites. Retrieved from https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites-0

[7] *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*, 610 UNTS art. 1 (1967), preamble and art I.

[8] United Nations Draft guidelines on the protection of the atmosphere (2021) Adopted by the International Law Commission at its seventy-second session, submitted to the General Assembly (A/76/10, para. 39)., Yearbook of the International Law Commission, 2021, vol. II, Part Two.

[9] Johnson, Christopher. 2020. "The Law of Outer Space: A Self-Contained Regime?" In Fifty Years of Space Law - Space Law in Fifty Years, edited by Philippe Achilleas and Stephan Hobe, 127–60. The Hague: The Hague Academy of International Law. https://brill.com/edcollbook/title/59584

atmospheric re-entry, can have adverse effects on the atmosphere. This process transfers waste from space to Earth, dispersing fine particulate matter into the atmosphere. Interestingly, the fragmentation of materials mirrors the fragmentation of legal norms [34]. Here, one material object operates and crosses the boundaries of two or more legal orders, either through controlled re-entry or uncontrolled re-entry, which upholds the legal fiction of displacing waste to cleanse a particular legal order (space), but at the expense of crashing in a competing legal order under protection from pollution (the atmosphere).

The knock-on effect of waste, pollution, and toxicity from one legal sphere to another legal sphere thus remains a challenge for the unity and cohesiveness of international law [35]. As ablation traverses a range of physical boundaries, a number of overlapping regimes are applicable, including the UNFCCC climate regime, the Ozone Treaty and its Montreal Protocol, a number of regional conventions on the protection of the atmosphere, and finally the law of the sea, since the protection of the atmosphere is intrinsically linked to the oceans, owing to the close physical interaction between the atmosphere and the oceans [36].

While the broad principles established in the OST were arguably sufficient in the early stages of space exploration, there is now a sense that the protection of space has overtaken the current international governance regime.[10] Obligations placed on states to protect the Earth's environment from space activities are limited, fragmented and inadequate given the current and anticipated extent of space activity. When identifying prospects and challenges for strengthening these obligations at the national and international level, we observe that environmental concerns are not directly addressed in international space law, which is primarily concerned with preserving outer space for peaceful purposes. In addition, it is difficult to identify relevant obligations in general international law, and creative interpretation is often required to apply these general obligations to space activities and its environmental impacts.[11] The result is a patchwork of obligations in international law, and significant gaps in terms of protection of the Earth's environment. Although states may be able to fill some of these gaps through national space laws and regulations, this approach may lead to inconsistent standards of environmental protection between states and encourage private actors to register space objects in "flag of convenience" states with the least onerous obligations.[12]

4.2.3 Fragmentation of authorities over legal delimitations

At the national level, non-legally binding "soft law" instruments may assist states to address some of the gaps and ambiguities in the space law framework. At the international level, challenges remain for strengthening the environmental obligations in relation to space activities. Besides the obvious geopolitical challenges, there are scientific uncertainties about the environmental impacts of space activities and therefore the kinds of harm the law should

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[10] McKinsey & Company and World Economic Forum "The role of space in driving sustainability, security, and development on Earth" (2022) at 20.

[11] Hopej, Kaja, and Katarzyna Malinowska. "Environmental law principles as guidelines for protecting the outer space." J. Agric. Env't L. 18 (2023): 18.

[12] It is important to note, however, that the risk of "flags of convenience" can be offset by market access requirements. For instance, when non-US domiciled satellite communications operator wish to serve the US market, they must conform to FCC space debris mitigation requirements as part of that market access licensing.

address. There is also legal uncertainty about the delimitation of Earth's air space (governed by national laws) and outer space (governed by international law), making it difficult to know how environmental harm from space activities should be regulated.

States and scholars disagree about whether it is necessary to define the border between air space and outer space in law, and, if so, how or where that boundary should be drawn.[13] The definition and delimitation of outer space is one of oldest issues on the agenda of the COPUOS,[14] and continues to be regularly debated.[15] International law does not define "the Earth's environment", nor "the atmosphere", and there is legal uncertainty about where the Earth's air space ends and outer space begins. These issues are significant because activities in air space are governed by national law,[16] whereas outer space is free for exploration and use by all states, subject to international law.[17]

Various approaches to the delimitation problem have been proposed,[18] however the Kármán line theory is the most widely preferred approach.[19] This is the "theoretical line beyond which an aircraft cannot fly by aerodynamic means alone unless it reaches the first cosmic velocity, namely, the velocity at which it can escape the Earth's pull and enter terrestrial orbit."[20] There are differing views on where this effect occurs, typically ranging from 80 km to 110 km above sea level.[21]

13 Report of the COPUOS Legal Subcommittee (60th session), *Promoting the discussion of the matters relating to the definition and delimitation of outer space with a view to elaborating a common position of States members of the Committee on the Peaceful Uses of Outer Space* UN Doc A/AC.105/C.2/L.302 (17 May 2017).

14 United Nations Committee on the Peaceful Uses of Outer Space Report of the Scientific and Technical Sub-committee on the work of its Fifth Session UN Doc A/AC.105/39 (6 September 1967).

15 Most recently, see: Report of the Chair of the Working Group on the Definition and Delimitation of Outer Space GA Res A/AC.105/C.2/2023/DEF/L.1 (2023).

16 See COPUOS Legal Subcommittee footnote n. 25.

17 Outer Space Treaty, art I.

18 For example, a spatialist approach (delimitation based on scientific criteria), a functionalist approach (activities regulated based on their objectives), and an arbitrary altitude of 100 km above mean sea level: *Promoting the discussion of the matters relating to the definition and delimitation of outer space with a view to elaborating a common position of States members of the Committee on the Peaceful Uses of Outer Space* UN Doc A/AC.105/C.2/L.302 (17 May 2017).

19 Stephan Hobe "Airspace" in *Max Planck Encyclopedia of Public International Law* (2019); and COPUOS Legal Subcommittee, *Definition and delimitation of outer space: Additional contributions received from States members of the Committee* UN Doc A/AC.105/C.2/2022/CRP.24 (6 April 2022) at 3; and COPUOS Legal Subcommittee footnote n 25.

20 *Definition and delimitation of outer space: Additional contributions received from States members of the Committee* UN Doc A/AC.105/C.2/2022/CRP.24 (6 April 2022) at 3.

21 *Ibid*, 3; and Andy Lawrence and others "The case for space environmentalism" (2022) 6 *Nature Astronomy* 428 at 428.

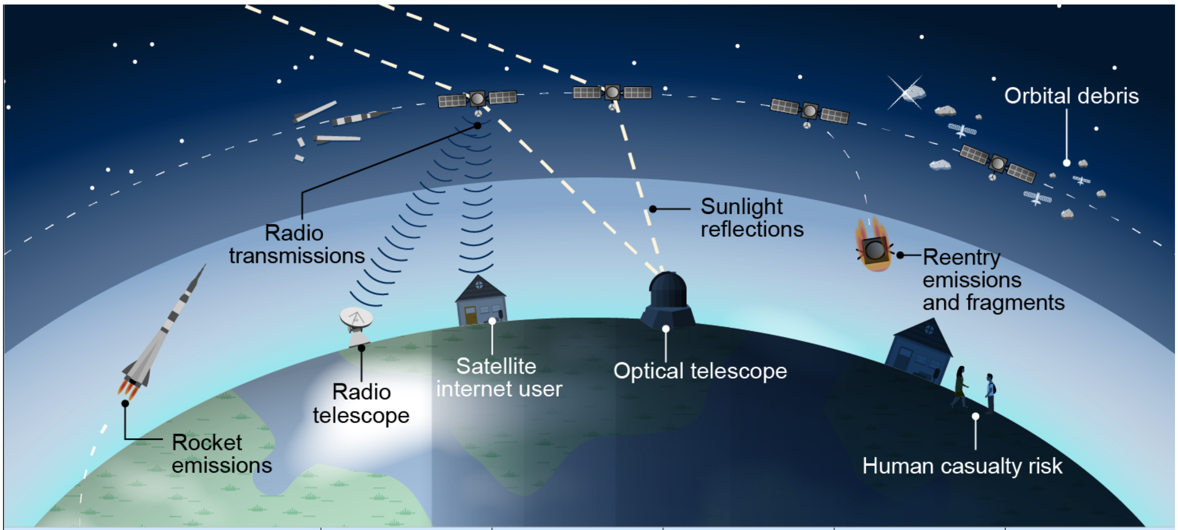
Most of the debate about delimitation has focused on a point somewhere above 80 km from the Earth,[22] and most of the environmental concerns with space activity are experienced below this point. For instance: ozone depletion occurs in the stratosphere (about 50 km above sea level); climate change occurs in the troposphere (about 10 km above sea level); and space debris causes potentially harmful contamination of land and damage to ocean ecosystems [37].

With ablation, the harm may originate above 80 km from Earth, with many satellites and mega-constellations orbiting Earth in the thermosphere (above 85 km from Earth) [37]. The harm may then persist at lower altitudes, and travel from the mesosphere (the third highest layer of atmosphere between 50 and 85 km) to the stratosphere, where the ozone layer sits between 15 km and 30 km above the earth and shields us and other living things from the sun's harmful ultraviolet radiation [37]. The primary concern appears to be with metal oxides, which catalyse chlorine activation and contribute to ozone depletion. However, other environmental impacts are also expected, such as changes in solar reflectivity and disruptions to Earth's magnetic field. There is also the problem of "noticeable delays between the beginning of the injection process when orbiting bodies are decommissioned and the eventual ozone-depletion consequences in the stratosphere" [38], which then interact at a later stage with the marine environment. *Which international authority, then, would be responsible for identifying, preventing and mitigating ablation the potentially harmful effects of atmospheric ablation of re-entering satellites? The UNFCCC Secretariat in Bonn? The Ozone Secretariat in Geneva? The International Maritime Organization in London?*

4.2.4 Fragmentation of authorities at a national level

Adding to the complexity of legal delimitation and legal fragmentation, national regulatory structures for space activities vary between jurisdictions, and multiple agencies are often involved in licensing and oversight of activities, as we shall see below. Spectrum and frequency licensing is often conducted in a different agency than oversight of space environment and space launch. Regulatory authorities may be in different organizations than technical expertise in space debris, spacecraft materials, and/or atmospheric science. For example, in the United States, the Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA); and the Federal Communications Commission (FCC) all have roles in different parts of licensing of commercial space activities; while the Department of Defense (DoD), NASA, and the National Science Foundation (NSF) have research roles related to the environmental, safety, and sustainability aspects of space activities. Terrestrial environmental regulation is largely the role of the Environmental Protection Agency (EPA) and the Council on Environmental Quality (CEQ).

[22] Andy Lawrence and others "The case for space environmentalism" (2022) 6 Nature Astronomy 428 at 428; and COPUOS Legal Subcommittee, *Definition and delimitation of outer space: Additional contributions received from States members of the Committee* UN Doc A/AC.105/C.2/2022/CRP.24 (6 April 2022) at 3.



Agency	Rocket emissions	Radio transmissions	Sunlight reflections	Orbital debris	Reentry emissions and fragments
Federal Aviation Administration	Oversight, Research			Oversight	Oversight
Federal Communications Commission		Oversight	Oversight	Oversight	Oversight
National Aeronautics and Space Administration	Research			Research	
Department of Defense				Research	
National Science Foundation			Research, Funding	Research	
National Oceanic and Atmospheric Administration	Research			Research	

Oversight Funding Research

Figure 11. U.S. Federal Processes That Consider Environmental and Other Effects of Large Constellations of Commercial Satellites [39].

In the UK context, space is governed by a range of agencies in charge of financing, regulating and monitoring space activities. The Department for Science, Innovation and Technology (DSIT) coordinates space exploration efforts, while the UK Space Agency (UKSA) is in charge of the broader national space policy. Under the 2021 National Space Strategy, DSIT has been responsible for coordinating civil space policy and UKSA has been responsible for developing and delivering civil space programmes across the UK space sector and with international space institutions. A July 2024 Government Audit concluded that meeting the objectives of the National Space Strategy was complicated by a lack of clarity on the aims, outcomes or priorities for the agencies to follow. “Three years later DSIT and UKSA are still in the early stages of identifying and developing the plans and capabilities needed to deliver the Strategy’s ambitions.” [40]

Coordination and consistency between regulatory agencies is often a challenge. In some cases, space and spectrum-related regulators are required to work together and coordinate during a licensing process; in other cases, regulatory authorities have limited contact; while in still others the level of cooperation fluctuates. Furthermore, in some jurisdictions, responsibilities for both space & spectrum licensing are given to actors with otherwise limited overall exposure to space [41]. Responsibility for management of terrestrial environment largely lies with agencies and authorities that are not part of the space licensing pathway. Atmospheric impact of space object re-entry largely falls into a gap in this network of agencies and coordination – with a lack of clarity on where the authority to impose regulatory requirements lies.

4.2.5 Perks and pitfalls of Environmental impact assessments

One commonly used regulatory tool to address effects on the terrestrial or human environment from space activities has been to require environmental impact assessments (EIAs) for certain space activities. Broadly speaking EIAs are used to assess the potential impact of a space activity on environmental management or protection values or standards (as set by the appropriate environmental regulatory authority in a jurisdiction), and if thresholds are exceeded, evaluate potential mitigation actions [42]. Outcomes of EIAs may result in binding restrictions, changes in licensing conditions, and/or non-binding advisory recommendations. In the United States EIAs are routinely applied to space launch activity by the Federal Aviation Administration (FAA) [43]. However, the Federal Communications Commission (FCC), which licenses any U.S. commercial spacecraft requiring use of the radio frequency spectrum, has applied a "categorical exemption" to satellites, exempting consideration of impact on the terrestrial environmental as part of licensing [43]. This policy was upheld by a U.S. federal court as recently as July 2024 [44]. In general, the regulatory ability to extend EIAs to cover the impact of atmospheric ablation of space object re-entry, remains unclear.

Similarly, in the UK, there are no explicit legal requirements to assess the impacts of ablation. Under the UK regime, a party is required to submit an Assessment of Environmental Effects (AEE), essentially an environmental impact assessment, as part of an application for a spaceport or launch licence. The UK's competent authority for purposes of this regime, the Civil Aviation Authority (CAA), issued guidance as to the contents of an AEE [25]. An AEE must contain evidence that the proponent has assessed the following in relation to its proposed space activities:

- population and human health;
- biodiversity (for example, ecology, flora and fauna);
- air quality;
- noise and vibration;
- water (for example, quantity and quality);
- marine environment;
- climate (for example, greenhouse gas emissions, impacts relevant to adaption);
- land, soils and peat;
- landscape and visual impact; and
- material assets and cultural heritage (including architectural and archaeological aspects) [26].

In the absence of clear requirements in the guidance to assess the impacts of ablation, ostensibly, proponents of space activities could assess ablation as part of its assessment of impacts under the "climate" limb of the AEE.

However, the precise assessment criteria of an AEE may become a matter of coordination between the UK's CAA (a branch of the UK Government in Westminster) and devolved administrations (for instance, the Scottish Environment Protection Agency, which is Scotland's principal environmental regulator under devolved administrative prerogative). Environmental impact assessments thus require complex co-ordination not only between legal and administrative authorities from global to national to regional scales, but also between industry groups working in different sectors and the wider civil society. Having ratified the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters, the UK has an international legal obligation to ensure public participation, which is a required component of an Assessment of Environmental Effects under the UK Space Industry Act [45].

4.2.6 Lack of Scientific Authority and Institutional Gaps in Awareness and Management of Ablation

These challenges are exacerbated by the lack of a technical authority to provide evidence on atmospheric ablation. The need for further research is clear, and some of that research is being conducted by various government and academic entities. However, there is currently no scientific body – analogous to the IADC for debris, the IAU for satellite reflectivity, or the IPCC for global temperatures – that can provide advice on the magnitude of the potential impact or the threshold at which mitigation might be required. The process by which regulators might ingest scientific and technical information on atmospheric ablations, and use that information to act, is unclear.

The ablating altitude, velocity, randomness of the mass of ablating object, varying composition etc. all make direct observation and data collection challenging. These complexities require sophisticated models and experimental setups that are difficult to standardise. The variability in atmospheric conditions and the specific parameters of each ablation event means that data can be inconsistent and challenging to replicate. Different studies often use varying techniques and assumptions, leading to inconsistent results.

As addressed in previous section 4.1, ESA's review of their two studies in 2021, the *ARA* [46] and the *ATISPADE* [47] studies, which analysed the effect of re-entering space debris on the Ozone layer, highlight a high level of uncertainty on aerothermodynamics and atmospheric chemistry-transport modelling and a lack of in-situ data to evaluate assumptions and models [48]. ESA also held a Workshop in January 2024 "Understanding the Atmospheric Effects of Spacecraft Re-entry" [49] The Workshop acknowledged the prevalence of a significant knowledge gap in accurately modelling the size distribution and chemical composition of particles emitted during ablation. The complexity of predicting these variables under high-temperature conditions makes it difficult to standardize models, leading to uncertainties in assessing environmental impacts. There is also the problem of a high number of spacecraft materials/systems which have not been characterized during re-entry and their high temperature chemistry is unknown due to lack of technical data [49]. These gaps in the quantification of materials and the qualification of by-products increase uncertainty in assessing and predicting the significance of environmental harm derived from ablation.

Schulz et al. [50] while addressing the risks posed by anthropogenic injections for the preservation of earth's atmosphere in the near future, also point out the uncertainties of their output due to insufficient data and a lack of regularity in scientific results. *Ferreira et al.* [51] in their recent study also highlight the uncertainties in the by-product generation and the lack of observational data to validate models. They also point out that this lack of evidence directly led to a delay in regulatory measures in the US.

Such scientific uncertainties and technical inconsistencies are compounded by the following situations:

- ***Inconsistent International Standards***: The lack of a technical authority results in varying standards and practices across different countries and organizations, complicating international cooperation.

- ***Policy Inertia***: Governments thus end up becoming victims of Policy Inertia, being reluctant to act on incomplete or uncertain information, leading to delays in the development of necessary regulations or international protocols. This lag can lead to inadequate mitigating regulatory measures against environmental side-effects, justified by the notion that any regulations formed might be premature.

Sirieys et al. [52] on this note propounds that while comparing the results of Montreal Protocol and Paris Agreement, the current lack of scientific evidence should not obscure discussions from beginning to identify viable solutions.

In September 2022 the United States Government Accountability Office (GAO) published a *Technology Assessment* on the topic of "*Large Constellations of Satellites: Mitigating Environmental and Other Effects*." This report considered technical and policy strategies to evaluate and mitigate potential environmental effects of large constellations including: orbital debris, disruption of astronomy, and emissions into the upper atmosphere (including from re-entries of satellites) [53]. Policy and regulatory challenges identified by the GAO related to atmospheric effects are listed in the following table.

Table 10. Challenges To Mitigating Atmospheric Effects of Large Constellations, As Identified by GAO [39]

Category	Challenges
Knowledge	"Scientists do not know the magnitude of effects from rocket launches and satellite reentry emissions."
Standards, regulations, and agreements	"Scientists and industry need established standard metrics of rocket launch and satellite reentry emissions to help guide potential regulations for rocket emissions in the upper atmosphere and for satellite designs."
Organization and leadership	"Establishing metrics or a database for rocket launch and satellite reentry emission requires organization between government and other entities."

One final organisational hurdle must also be addressed. Regulators often have limited resources to address development of new scientific knowledge or technical mitigation strategies for emerging problems. Regulators may not have the ability to assign passing internal researchers or staff to track potential environmental and other effects of satellites, meaning external information is important. However, regulators may also face policy or administrative barriers in using third-party information or models to inform regulatory requirements. Regulators also are concerned with timing – there is a need to balance the need for scientific evidence to inform policy with the need for timely decision-making [54] [54], [55].

4.3 Appendix: Potential Relevant Technical Authorities

While there is not a specific technical/scientific body specifically focused on atmospheric impacts of space activities, there are existing forums that could serve a contributing role, including the Scientific and Technical Subcommittee (STSC) of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS); the Committee on Space Research (COSPAR), the Inter-Agency Space Debris Coordination Committee (IADC), and space agencies such as the European Space Agency (ESA). Brief profiles of these organizations are provided below, along with additional discussion provided in TN02.[23]

4.3.1 COPUOS

While primarily a diplomatic and governance body, the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) has a Scientific and Technical Subcommittee (STSC). STSC provides input and consideration to UNCOUPOUS, on scientific and technical aspects of space activities, making it potentially a key forum in discussing the issues of atmospheric impacts from re-entering space objects, and related international governance approaches, to the international table. However, the topic of atmospheric impacts from re-entering space objects has only been briefly mentioned in statements from member states at COPUOS and is not currently a formal item under consideration by either the full Committee or its two subcommittees (STSC) and the Legal Subcommittee (LSC).

COSPAR

One of the few organisations that are investigating the environmental effects of space activities is the Committee on Space Research (COSPAR). The Purpose of COSPAR is the promotion of international scientific research in space, exchange of results and collaboration on space research. COSPAR achieves these objectives through the organization of scientific assemblies, publications, or any other means.[24] The COSPAR Panel on Potentially Environmentally Detrimental Activities in Space (PEDAS) has conducted research into pollution of Earth's atmosphere from re-entries. The COSPAR Panel on Planetary Protection is focused on protection against extra-terrestrial contamination, but offers a process example relative to the challenges assessed in this study. COSPAR is further discussed in TN02.[25]

Panel on Planetary Protection (PPP)

[23] See TN02, Section 3.1.2 "The Polycentric Space Governance Regime" & Section 3.1.4 "Examples Where Technical and Scientific Information Has Informed Policy in the Field of Space Sustainability".

[24] See COSPAR activities online: https://cosparhq.cnes.fr/

[25] See TN02, Section 3.1.2 "The Polycentric Space Governance Regime" & Section 3.1.4 "Examples Where Technical and Scientific Information Has Informed Policy in the Field of Space Sustainability".

COSPAR's Panel on Planetary Protection (PPP) is primarily concerned with Biological interchange and contamination in course of space exploration.[26] While extraterrestrial concerns are a critical component of responsible space exploration, the preservation of Earth's atmosphere from the impacts of space activities, such as atmospheric ablation, does not fall directly within this scope. While "forward contamination" (contamination of other planets) and "backward contamination" (contamination of Earth by extraterrestrial materials) are addressed, it does not extend to addressing the potential of environmental degradation on Earth due to space activities (which is addressed in the scope of other elements of the COSPAR structure).

Panel on Potentially Environmentally Detrimental Activities in Space (PEDAS)

COSPAR's Panel on Potentially Environmentally Detrimental Activities in Space (PEDAS) "acts on an ad hoc basis to evaluate questions of environmental impacts by space activities alone or together with other relevant organizations primarily to advise the international community, e.g., the Committee on the Peaceful Uses of Outer Space (COPUOS) of the United Nations." Topics considered by the panel focus on impacts to the terrestrial and planetary environments from space activities.[27]

4.3.2 IADC

The IADC is responsible for coordinating international efforts related to space debris mitigation [56]. The 2024 Report on the Status of the Space Debris Environment describes the challenges associated with space debris re-entry. However, the mandate of the IADC is to mitigate debris congestion and fragmentation, and does not involve the Committee in providing guidance on impacts from atmospheric ablation.

4.3.3 ESA-ESTEC

The European Space Agency (ESA), through its European Space Research and Technology Centre (ESTEC), has recently shown a growing awareness of the complexities involved in ablation processes. Through a workshop focusing on space debris re-entry and ablation [49]

[26] Scope and Objective of the Panel on Planetary Protection: *"The Panel on Planetary Protection (PPP) is concerned with biological interchange in the conduct of solar system exploration and use, including: (1) possible effects of contamination of planets other than the Earth, and of planetary satellites within the solar system by terrestrial organisms; and (2) contamination of the Earth by materials returned from outer space carrying potential extraterrestrial organisms. The primary objective of the Panel within COSPAR is to develop, maintain, and promulgate clearly delineated policies that provide specific requirements as to the standards that must be achieved to protect against the harmful effects of such contamination"* https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-planetary-protection-ppp/#scope

[27] "PEDAS is concerned with perturbations of the terrestrial and planetary environments resulting from space activities. Typical examples are: space debris in Earth orbit, light pollution from satellites, pollution of the Earth's atmosphere by rocket launches and re-entries, perturbation of the lunar environment by all human activities as well as possible perturbation of the Martian environment by space activities." While the words "and re-entries" can still be found on the COSPAR website: https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-potentially-environmentally-detrimental-activities-in-space-pedas/, they were omitted in the Open Access Government publication "COSPAR - Committee on Space Research." *Open Access Government*, 27 June 2022, in the "Space Debris" section outlining PEDAS concerns: https://www.openaccessgovernment.org/ebook/cospar-committee-on-space-research/137732/. Whether intentional or not, the omission is nevertheless significant to this analysis.

which demonstrated a growing awareness of the complexities involved in ablation processes and the need to understand its possible effects on the Earth. The workshop concluded that current regulations and mitigation strategies are insufficient to address the challenges posed by atmospheric ablation of space debris.

The review of key reports reveals significant institutional gaps in addressing the uncertainties related to atmospheric ablation. While there is recognition of the broader challenges associated with space debris re-entry, the specific issues of ablation as a whole is turned a blind eye to, including the difficulties in measuring and modelling its effects. This lack of detailed engagement with ablation uncertainties represents a critical gap that could hinder the development of effective international policies and regulations.

4.3.4 Governance Gaps In Interaction of Technical Authorities

A potential environmental problem does not automatically result in the development of governance frameworks or the establishment of competent authorities even if such problem is scientifically proven. The governance process is often long and complex, involving various stages of scientific validation, policy development, and international negotiations for consensus.[28] An illustrative example of this drawn-out process can be found in the history of how the space community addressed the issue of space debris, particularly with regard to Kessler's syndrome and LTS.

Kessler's findings in 1978 [57] highlighted the potential for a self-sustaining cascade of collisions where each such collision generates more and more space debris. As the amount of space debris in orbit grows, the increasing density of objects increases the number of collisions between space debris, resulting in the generation of additional debris at a rate faster than can be naturally removed from orbit by the Earth's atmosphere. Although this theory was scientifically acknowledged and backed by empirical studies over the following years, the awareness of the problem alone was not adequate to spur international collaboration or regulatory measures. It took 15 years after the theory's initial publication for the international community to establish the IADC in 1993, a forum where space agencies could collaborate on the common issue of space debris. This delay exemplifies the gap in regulatory response to emerging scientific evidence. Furthermore, the first draft of the IADC Space Debris Mitigation Guidelines was released in 2002, 24 years after Kessler's initial paper. Although this matter was emphasized in the UNISPACE-III Report of 1999 [58] and COPUOS's STSC acknowledged and discussed this topic since 2002 [59], these guidelines were not formally adopted by COPUOS until 2007 [60]. In sum, the Scientific-Policy gap lasted *29 years*.

Drawing from this precedent, atmospheric ablation may fall into a similar trap with policy playing catch-up to the scientific analysis. This Scientific-Policy gap will inevitably result in unchecked environmental harm until the harm evolves to a point where it can no longer be ignored.

[28] After the establishment of a working group in 2010 for Long Term Sustainability in Outer Space Activities, It took the Working Group 9 years simply to achieve consensus for the 29 guidelines proposed.

5 New Space Policy Framework

While the rapid growth of space activities has brought unprecedented benefits to society, it has also introduced significant environmental challenges. One such issue is the potential environmental impact of satellite ablation during atmospheric re-entry at the end of their mission. This section outlines elements for developing new space policy framework[s] to assess the environmental implications of post-mission atmospheric ablation, and provide the foundation for policy and regulatory strategies to mitigate those potential impacts. The policy framework would seek to catalyse further research into the magnitude of potential effects, and their sources, with a goal of minimising the pollution of the upper atmosphere, and other regions of the terrestrial environment, from the atmospheric disposal of spacecraft at end-of-life (EoL). It supports global space industry actors, the UK Space Agency, other national space agencies, and international space cooperation and governance bodies in working towards the sustainable use of outer space. The framework aligns with international guidelines and principles while incorporating the UK's unique context, history, and developmental path in space exploration and utilisation.

This new space policy framework includes a wider, contextualised **policy vision** that focuses on, and seeks to address, both Earth-based and space-based dimensions of the sustainable use of outer space. This vision is informed by a number of guiding principles established in international and national-level guiding principle documents. It can be expanded by policies and legislation stemming from the UK’s unique context, history and development path in the sustainable use of outer space. The **guiding principles of** the new space policy framework underpin the design and operation of a strategy to mitigate the potential and expected environmental impact of EoL satellite disposal through atmospheric burning (‘ablation’). The policy's **goals and objectives** will set specific targets to be achieved through new guidelines for satellite disposal and materials. An **implementation strategy** will outline the necessary actions to mitigate the impact of ablation, including considerations for satellite design, composition, and operation. It will also address governance and regulatory measures at international, regional, and national levels, identifying the best approaches to ensure the adoption of these practices.

This policy framework, therefore, will reflect the UK's commitment to leading in the sustainable use of outer space by addressing the environmental impacts of satellite re-entry. By aligning with international principles and leveraging national capabilities, the UK aims to ensure that space activities contribute positively to global environmental sustainability and the long-term viability of space as a shared resource.

5.1 Vision

This new space policy framework aims to lead the world in pioneering sustainable space practices by ensuring that all spacecraft missions are designed and managed to minimise harmful environmental impact, enhance the long-term sustainability of outer space, and protect both our planet and the space environment for future generations. This vision builds on the UK Space Agency’s National Space Strategy [61] and the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) long-term sustainability guidelines [62] for the sustainable use of outer space.

The **vision of this policy framework** is to minimise the harmful terrestrial environmental impacts of space debris and the end-of-life (EoL) disposal of spacecraft through atmospheric ablation. This will be achieved by implementing practices where all spacecraft operators and manufacturers receive technological guidance on spacecraft design, material selection, and low-cost controlled (or semi-controlled) re-entry methods. These practices aim to reduce harmful emissions during the disposal of spacecraft at the end of their missions, ensuring a cleaner and safer space environment.

5.2 Guiding Principles

The guiding principles for achieving sustainable EoL spacecraft and debris disposal through atmospheric re-entry support the development of a clear and coherent policy framework on spacecraft design and post-mission disposal. This framework should be informed by international legal principles such as the precautionary principle, due regard, and the minimisation of transboundary harm. An evidence-based approach is essential to minimising and preventing the harmful environmental impacts of EoL spacecraft re-entry. The policy framework must also empower all spacecraft manufacturers and operators to adopt sustainable practices.

The following specific policy principles must underpin any policy, strategy, or framework supporting sustainable spacecraft disposal through atmospheric re-entry:

- **Environmental Stewardship:** Embrace a commitment to environmental responsibility by reducing harmful by-products and debris from satellite disposal undertaken by atmospheric re-entry, in order to mitigate the potential significant harm that these activities might pose o the Earth's atmosphere or ecosystems.
- **Innovation and Excellence:** Foster innovation in space technology and mission design to develop advanced solutions that prioritise sustainability and environmental protection throughout the satellite lifecycle.
- **Global Leadership:** Position the UK as a global leader in sustainable space practices, setting benchmarks and inspiring other nations to adopt similar commitments to the sustainable use of outer space.
- **Collaborative Efforts:** Promote international cooperation and partnerships to harmonise standards and practices, facilitating a collective effort towards a cleaner, safer space environment.
- **Safety and Responsibility**: Ensure that all space operations associated with spacecraft and debris disposal through atmospheric re-entry prioritise the safety of both space assets and human life, adopting responsible practices that limit environmental harm.

5.3 Policy Goal and Objectives

The goal of the policy framework is to minimise the harmful environmental impact of EoL disposal of spacecraft and debris through atmospheric re-entry, while supporting the broader objective of sustainable use of space across all sectors, including spacecraft manufacturers and operators. It focuses on mechanisms for integrating scientific information and knowledge into policymaking, prioritising funding for further research, and addressing additional gaps we identify in the policy and legal realms. It also considers steps necessary for putting into place an appropriate regulatory approach that engages stakeholders across the ecosystem in developing and implementing mitigation strategies.

The policy framework's **Five specific goals** to realise the vision of this new space policy are:

- **Prevent significant harm to the environment**, by examining what might be considered an appropriate and reasonable re-entry procedure, standard or rule, utilising materials and technologies that pose no threat to Earth's atmosphere, based on technological changes and scientific developments. In designing measures, states shall take into account the degree of risk, the importance of the activity, the availability and costs of means to prevent or minimize harm, and the standards of prevention which the state likely to be affected applies to the same or comparable activities, as well as standards applied in comparable regional or international practices. States concerned shall seek solutions based on an equitable balance of interests. **Sustainable Space Ecosystem:** Create a sustainable space ecosystem where the EoL disposal of spacecraft and debris does not significantly contribute to the contamination of the upper atmosphere and global climate change, ensuring the long-term viability and accessibility of outer space for all users.
- **Innovative Technology Leadership:** Lead the development and implementation of advanced technologies that enable environmentally sustainable spacecraft design, minimising the generation of metal oxides and particles during atmospheric re-entry. Position the UK as a hub for green space innovation by promoting sustainable re-entry disposal practices.
- **International Best Practices:** Establish and promote best practices for spacecraft and debris re-entry disposal on a global scale, collaborating with international bodies to create common guidelines that all spacefaring nations can follow.
- **Educational and Economic Growth:** Inspire educational initiatives and economic opportunities within the UK by fostering a culture of sustainability in space exploration, driving growth in green technologies and environmental sciences.

The policy framework's objectives relate to the five guiding principles presented in the Section 2.2. In line with these principles, the **Four objectives** are to develop policies that:

- **Environmental Protection:** Minimise the environmental impact of satellite re-entry by developing and implementing technologies for low-cost controlled or semi-controlled re-entry and material design that reduces harmful emissions (by-products of atmospheric ablation) and debris.
- **Sustainable Use of Outer Space:** Promote the sustainable use of outer space by ensuring that satellite operations and end-of-life disposal practices minimise the environmental impacts of ablation while still encouraging responsible post-mission disposal.

- **International Collaboration:** Engage with international partners and organisations to harmonise spacecraft and debris re-entry disposal standards and practices, contributing to global efforts in space sustainability.
- **Innovation and Research:** Support research and innovation in green technologies for spacecraft manufacturing and re-entry disposal, fostering advancements that minimise harmful environmental impacts.

To achieve the goals and objectives, the policy framework presents **five key elements** needed to implement the new space policy frameworks in order to inform spacecraft manufacturing and operation:

- **Policy Integration:** Integrate sustainable re-entry disposal practices into all national space policies and regulatory frameworks, ensuring consistent application across all missions and projects.
- **Research and Development:** Invest in research and development programs focused on sustainable space technologies, supporting innovations that reduce harmful environmental impacts and enhance mission safety.
- **Public Awareness:** Enhance public awareness about the importance of sustainable space practices by fostering a deeper understanding and support for environmental protection in space activities. This involves effectively communicating scientific uncertainties to the public, reflecting the complexity of these issues, while also highlighting the benefits of space exploration.
- **Capacity Building:** Develop the skills and expertise within the UK space sector to design, build, and operate spacecraft with minimal environmental impact, fostering a knowledgeable and capable workforce.
- **Global Standards Adoption:** Work towards the adoption of international standards for sustainable spacecraft and debris re-entry disposal, contributing to global efforts in maintaining a clean and safe space environment.

5.4 Policy Measures & Implementation Strategy

The policy framework presents the need for standards for spacecraft manufacturers and operators to adapt their spacecraft design and post-mission disposal methods. It also outlines the linked policy measures needed to support the achievement of these standards. These standards will serve as indicators of sustainable and responsible space usage and a means to prevent or minimise harmful environmental impacts from disposing of spacecraft and debris via atmospheric re-entry.

- **Design and Manufacturing Standards:** Establish national/international standards for satellite design and manufacturing that prioritise materials and technologies minimising harmful by-products and debris during atmospheric re-entry.
- **Re-entry Protocols:** Develop protocols for controlled/semi-controlled/un-controlled re-entry of spacecraft and debris to reduce the environmental risk at upper atmosphere.

- **Regulatory Framework:** Strengthen the regulatory framework to enforce compliance with environmental standards for spacecraft and debris re-entry, including penalties for non-compliance and incentives for sustainable practices.
- **Public and Private Sector Collaboration:** Foster collaboration between government, industry, and academia to share knowledge, resources, and best practices for sustainable satellite re-entry.
- **Monitoring and Reporting:** Implement a monitoring and reporting system for satellite re-entry disposal events, providing transparency and accountability in environmental impact assessments.

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